

IceCube results

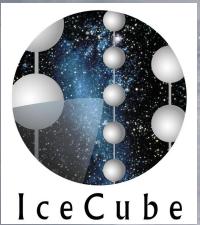
Albrecht Karle

University of Wisconsin-Madison

For the IceCube Collaboration

Santa Fe, August 2013

Introduction
Detector, events, techniques
New results with contained vertex events
Discussion, other channels
A few comments on low energies



IceCube Science Goals

- Search of high energy astrophysical neutrinos and their sources at energies $> \sim\text{TeV}$ ($10^8 - 10^{18}$ eV) - *This talk will focus on this topic and evidence found for astrophysical neutrinos.*

Talks at TeVPA this week:

- A. Ishihara: Probing cosmic-ray origin with the cosmogenic neutrino ~~searches with IceCube~~ [IceCube schedule](#)
 - C. Kopper: Analysis of the High-Energy Starting Events in IceCube
 - J. Feintzeig: Searches for Point and Extended Sources of Neutrinos with the IceCube Detector
 - J. Kiryluk: IceCube cascade results
 - I. Taboada: Search for correlation of high-energy starting events in IceCube with GRBs
 - M. Richman: Search for Prompt Neutrino Emission from Gamma Ray Bursts with IceCube
- See also talks by Ahlers, Yoshida, Stecker and Laha on interpretation of recent observations

- Atmospheric neutrinos, cosmic ray physics and associated particle physics
- Search for indirect dark matter
- Supernova core collapse neutrino detection
- Searches for other rare ‘exotic’ phenomena, eg. magnetic monopoles
- Associated science topics such as glaciology

Cosmic Rays and Neutrino Sources

Can neutrinos reveal origins
of cosmic rays?

$$p\gamma \rightarrow p\pi^0, n\pi^+$$

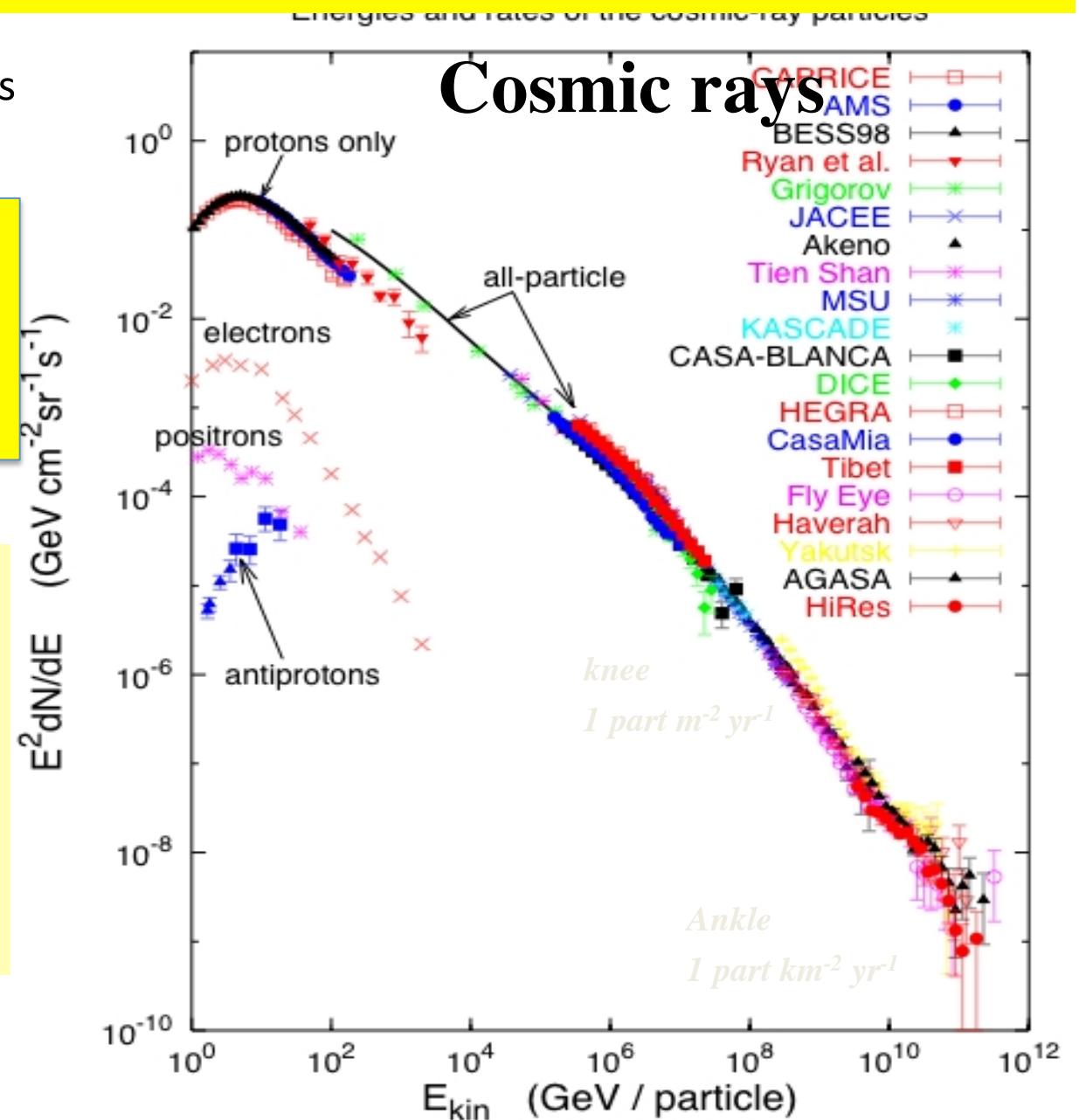
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Cosmic ray interaction in accelerator region

Prime Candidates

- SN remnants
- Active Galactic Nuclei
- Gamma Ray Bursts



Neutrino production from cosmic rays on known targets.

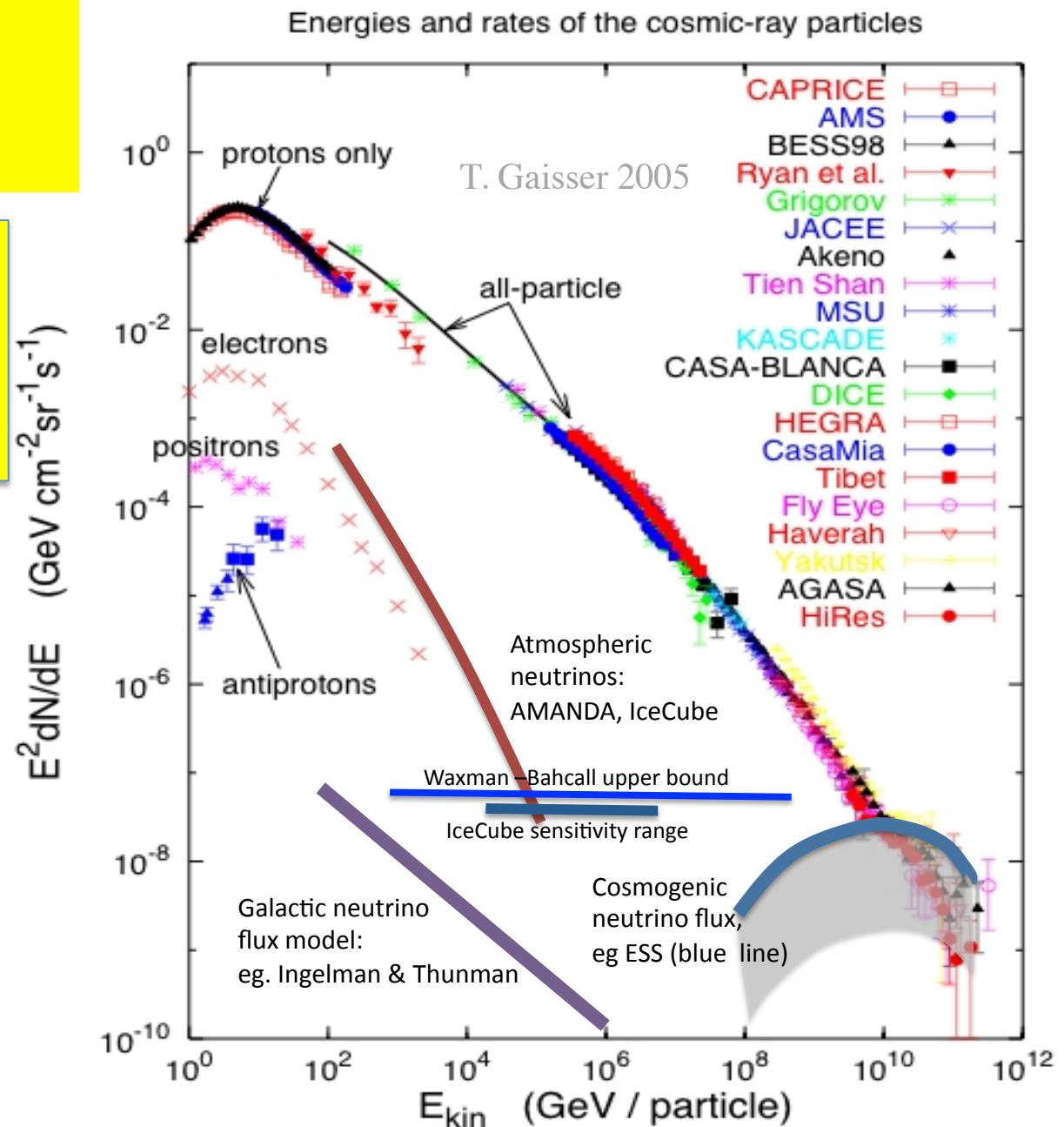
$$pp \rightarrow NN + pions; \quad p\gamma \rightarrow p\pi^0, n\pi^+$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

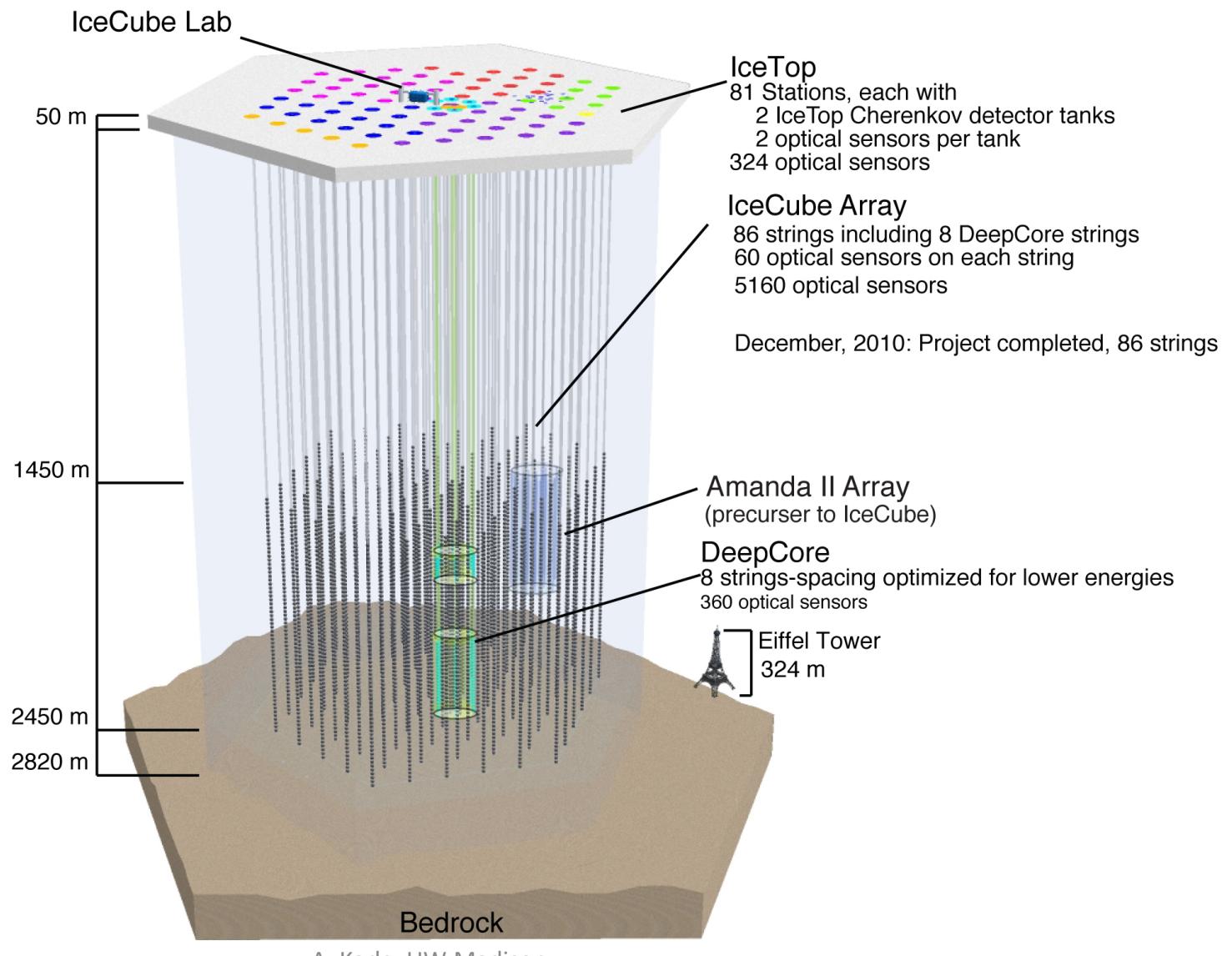
Known targets:

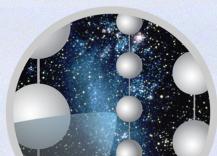
- Earth's atmosphere: Atmospheric neutrinos (from π and K decay)
- Interstellar matter in Galactic plane: Cosmic rays interacting with Interstellar matter, concentrated in the disk
- Cosmic Microwave background: UHE cosmic rays interact with photons in intergalactic photon fields.



The IceCube Neutrino Observatory

- Total of 86 strings and 162 IceTop tanks;
- Completion with 86 strings: December 2010
- Full operation with all strings since May 2011.





The IceCube Collaboration



International Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)

Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)

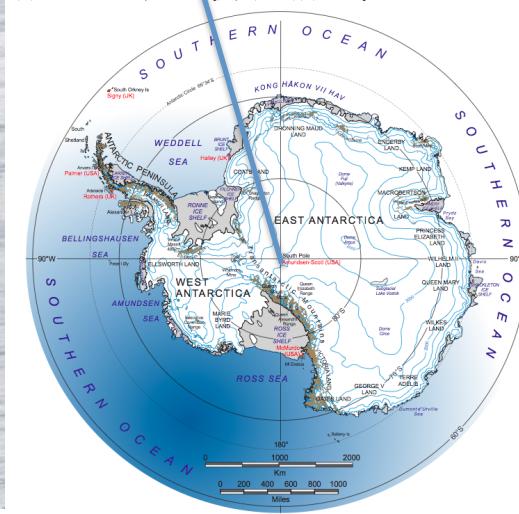
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)

University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

South Pole Station

South Pole

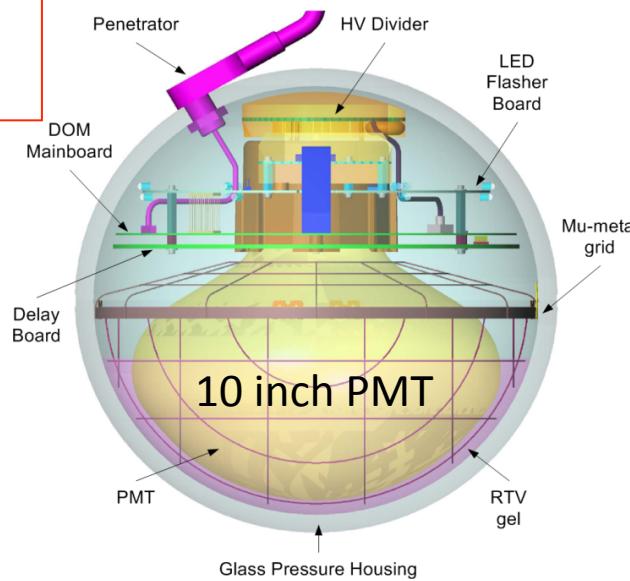
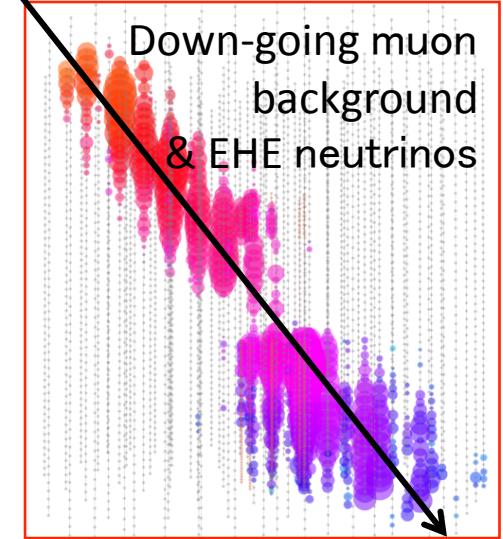
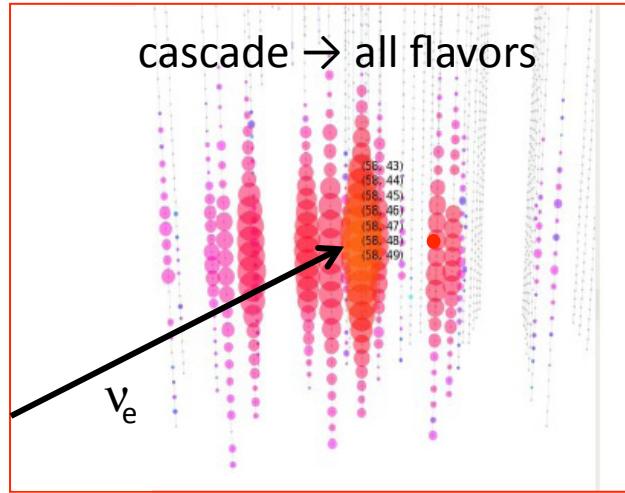
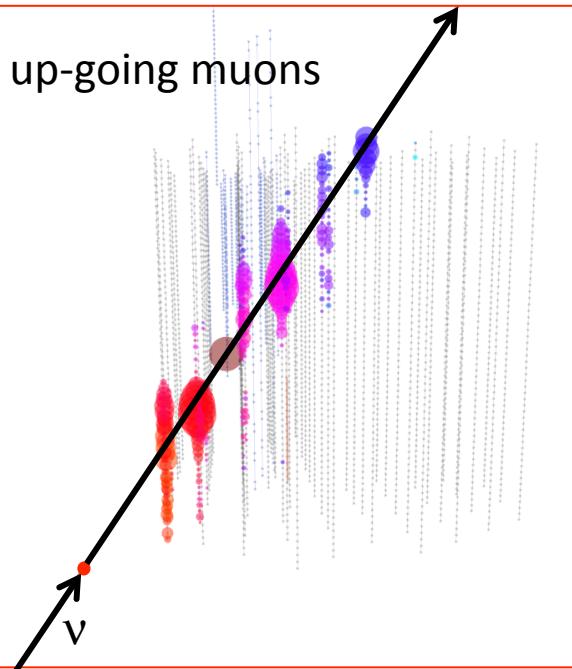
IceCube Lab



IceCube Laboratory



Detection Methods



light collection by DOMs

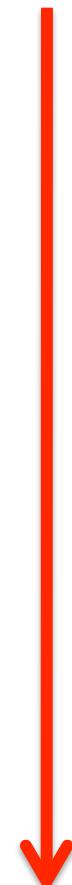
DOM Low Noise rate (500 Hz)
(300 Hz with deadtime)

High reliability, very few
sensor issues per year.

Gains very stable to <0.3%.

20 years of construction history of AMANDA and IceCube

1991



2011

Season	Campaign	Sensors cum.	Strings	Depth (m)	Neutrinos per day	Resol. @100TeV
1991-1992	Exploratory	few		Shallow	-	
1992-1993						
1993-1994	AMANDA-A	80	4	800-1000	-	
1994-1995						
1995-1996	AMANDA-B4	86	4	1500-1950	~ 0.01	
1996-1997	AMANDA-B10	206	6/10	1500-1950	~ 1	4 °
1997-1998						
1998-1999	AMANDA-II	306	3/13	1500-1950		
1999-2000	AMANDA-II	677	6/19	1500-1950	~ 5	2 °
2001-2002						
2002-2003						
2003-2004	IceCube prep.					
2004-2005	IceCube 1	60	1/1	1450-2450		
2005-2006	IceCube 9	540	8/9	1450-2450		
2006-2007	IceCube 22	1320	13/22	1450-2450	18	1.5 °
2007-2008	IceCube 40	2400	18/40	1450-2450	40	0.8 °
2008-2009	IceCube 59	3540	19/59	1450-2450	120	0.6 °
2009-2010	IceCube 79	4740	20/79	1450-2450	180	0.4 °
2010-2011	IceCube 86	5160	7/86	1450-2450	>200	0.4 °

Neutrino Skymaps

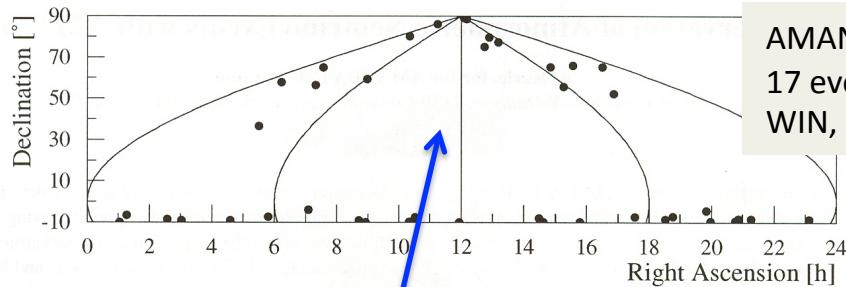
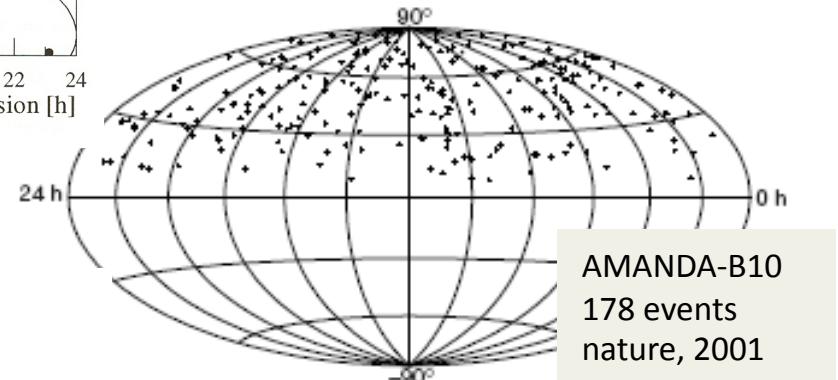
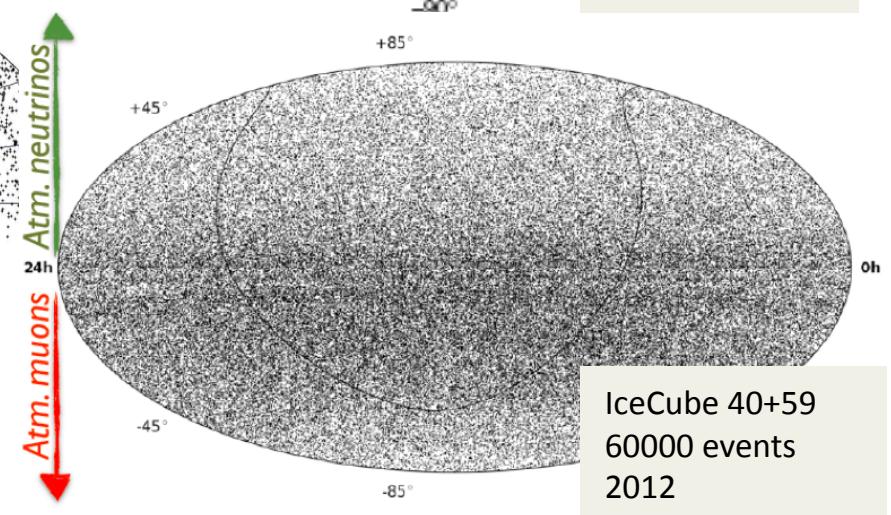
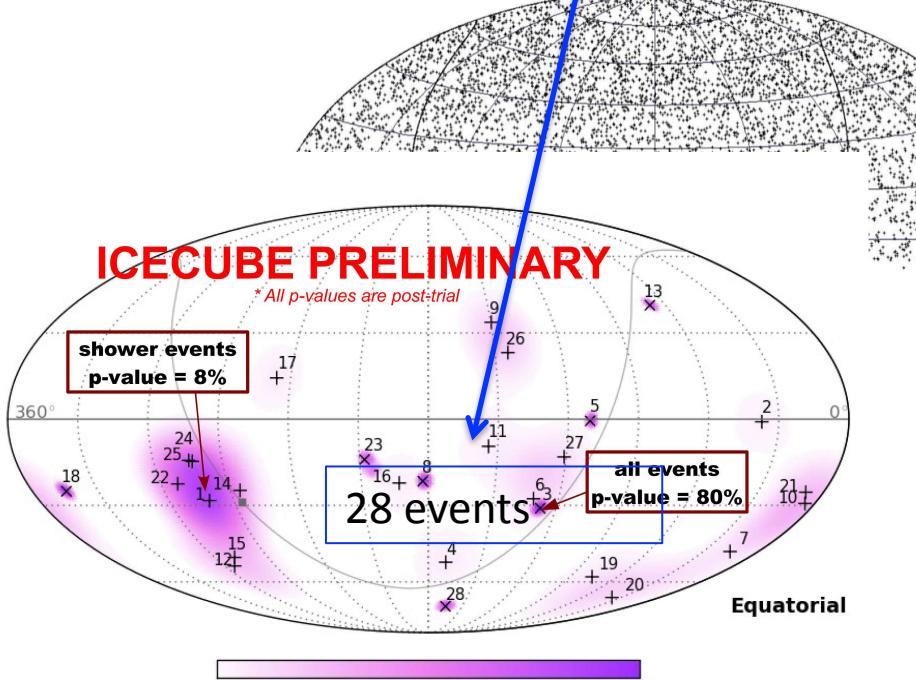


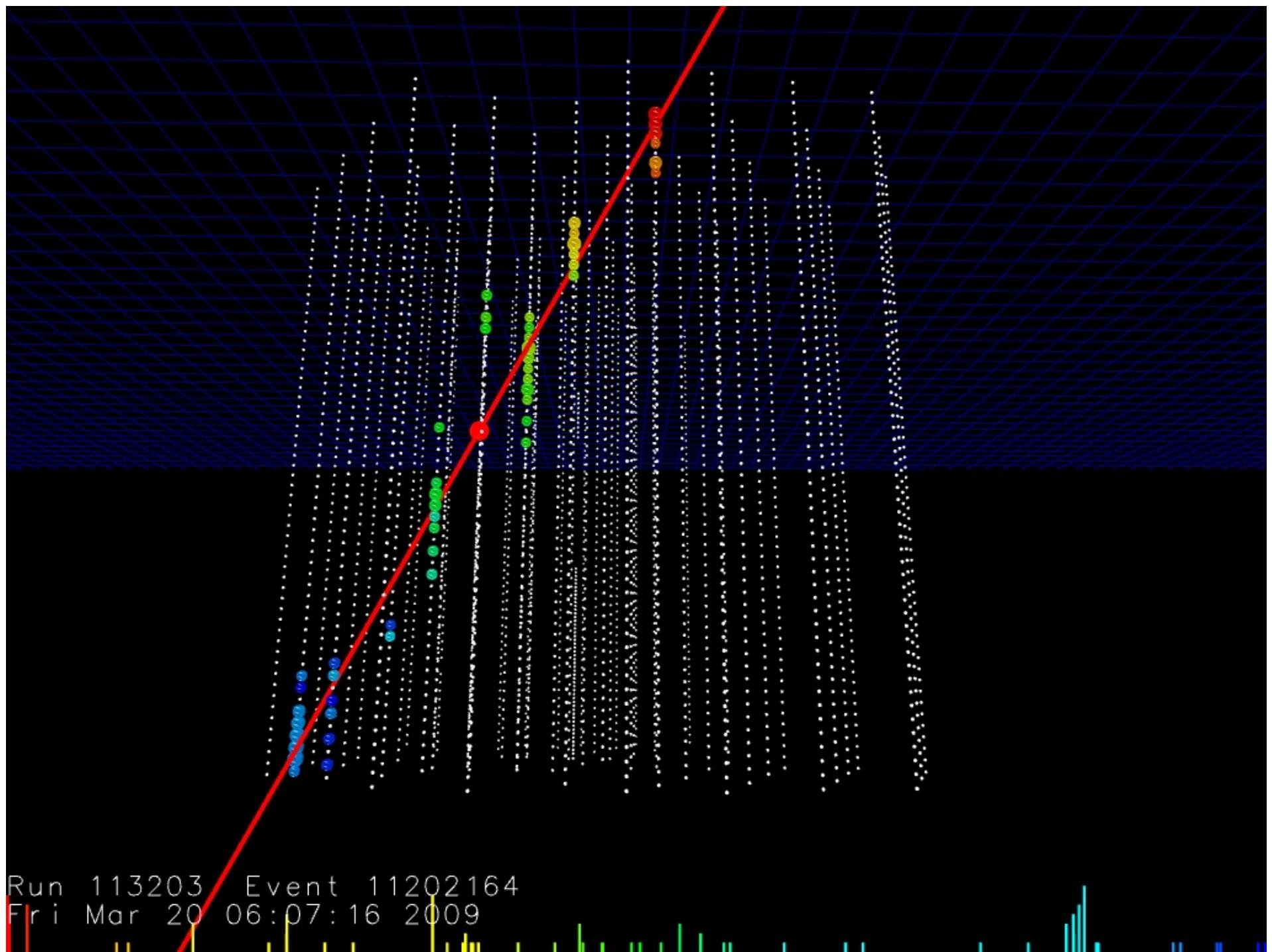
Figure 2: Sky plot of all events that pass level 4 quality cuts.

AMANDA-B10
17 events
WIN, 1999

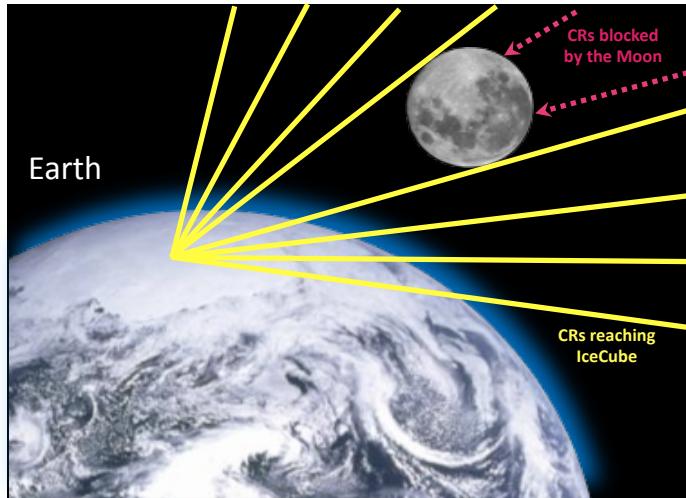


AMANDA-B10
178 events
nature, 2001





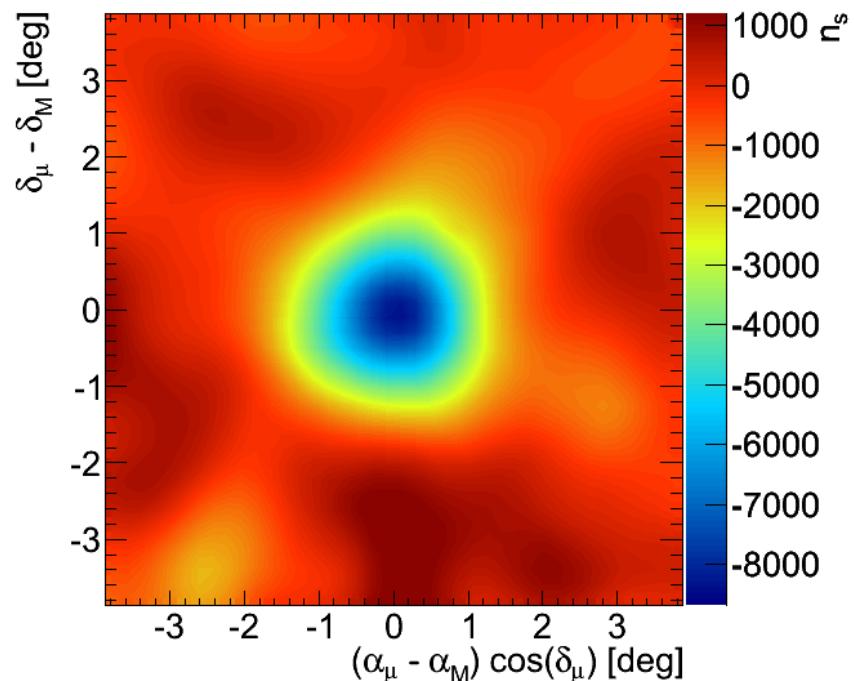
Moon shadow



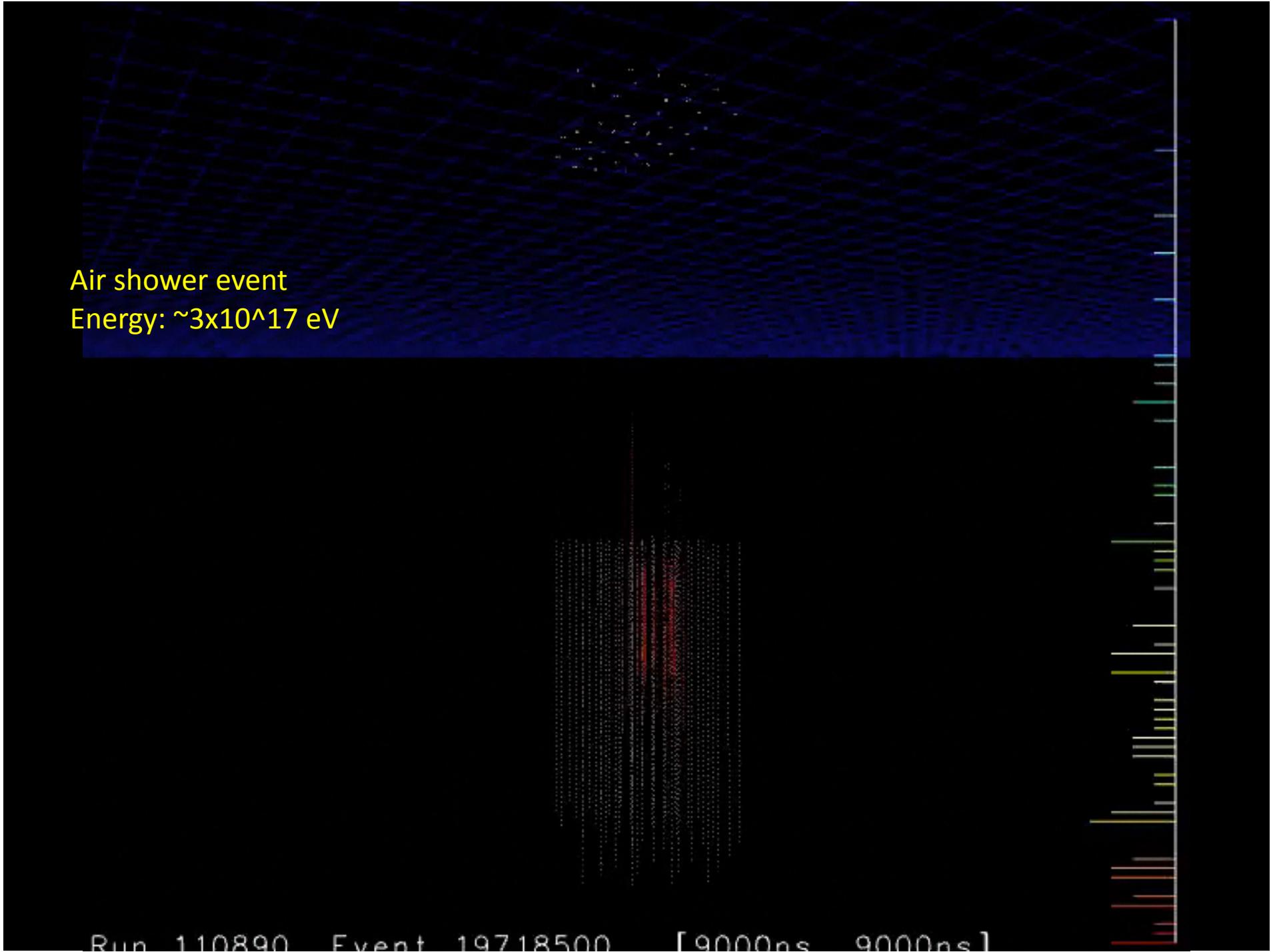
- Moon blocks cosmic rays coming from its direction.
→ deficit of muons from direction of moon.

Deficit: ~ 8700 events

Significance: 13.9σ



Observed shadow exactly matches expectations
on pointing ($<0.1^\circ$) and angular resolution (0.7° for these events).



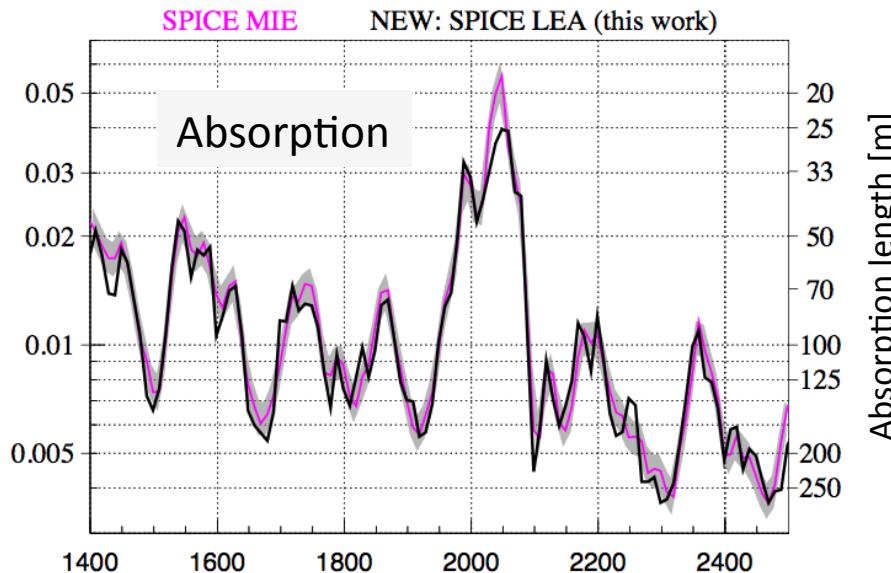
Air shower event

Energy: $\sim 3 \times 10^{17}$ eV

Run 110890 Event 19718500 [9000ns 9000ns]

Ice and detector response – → reduce systematic errors!

1. Vertical structure of ice parameters



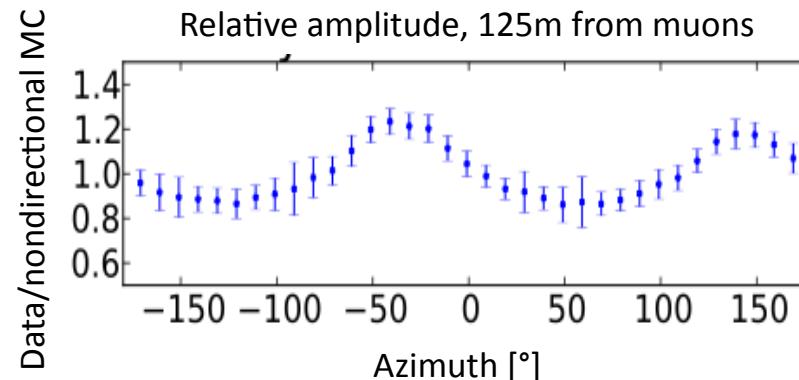
Scattering (eff.): 20 – 50 m
Absorption: 100 – 200 m

Measurement of South Pole ice transparency with the IceCube LED calibration system,

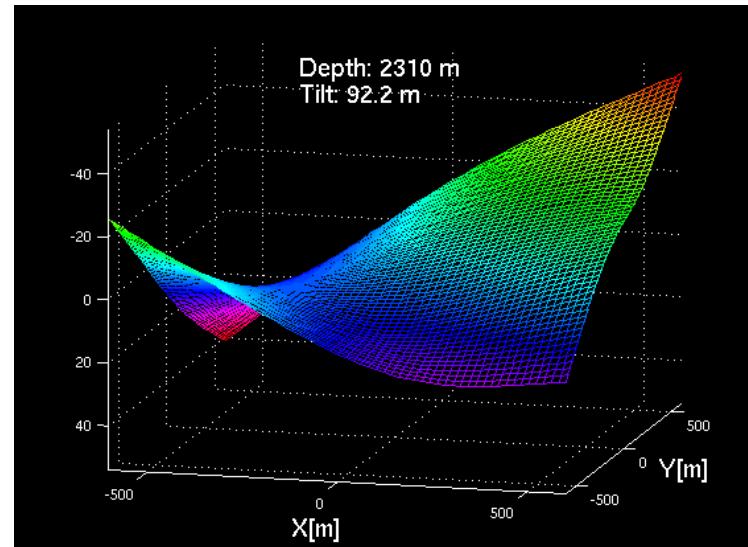
Aartsen et al., (IceCube Coll.), NIMA55353
<http://arxiv.org/abs/1301.5361>

2. Azimuthal variation in of scattering

Less scattering in direction of ice flow:
→ up to ~10% /100m variation in amplitude



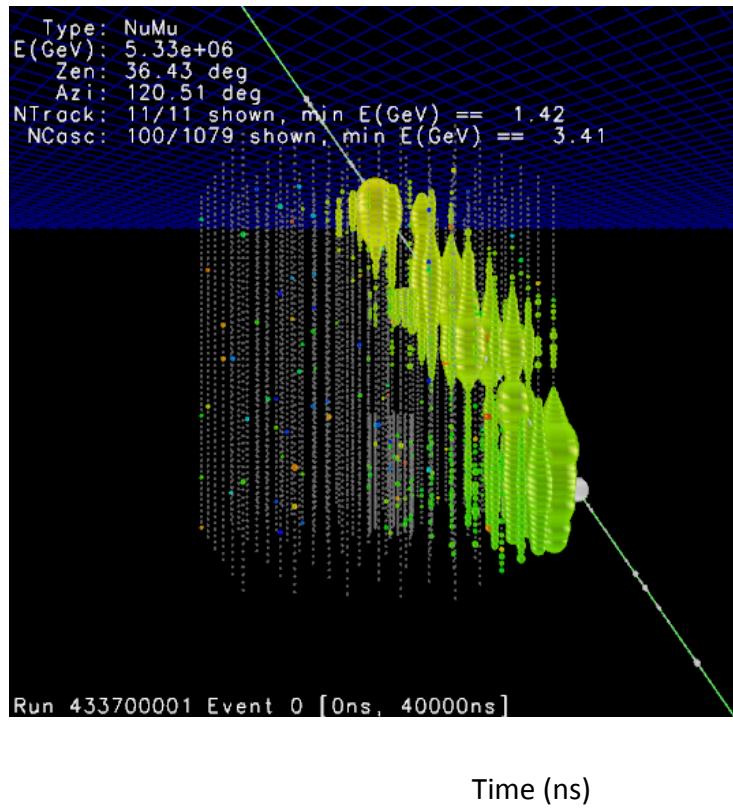
3. Ice layers are tilted – not planar



Improving event reconstruction: muons

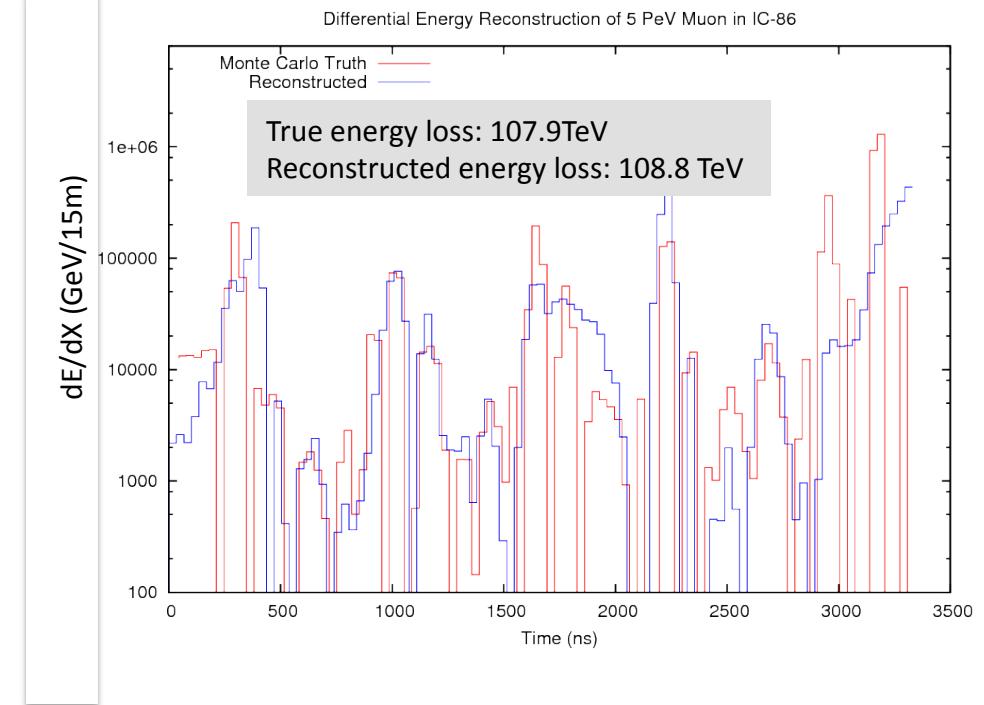
Simulated Muon of 5 PeV energy

Improved tools allow to resolve stochastic energy losses along the km long tracks.



Muon energy resolution:
rms of $\log(E)$: ~0.3 - 0.25 for $E > 100$ TeV

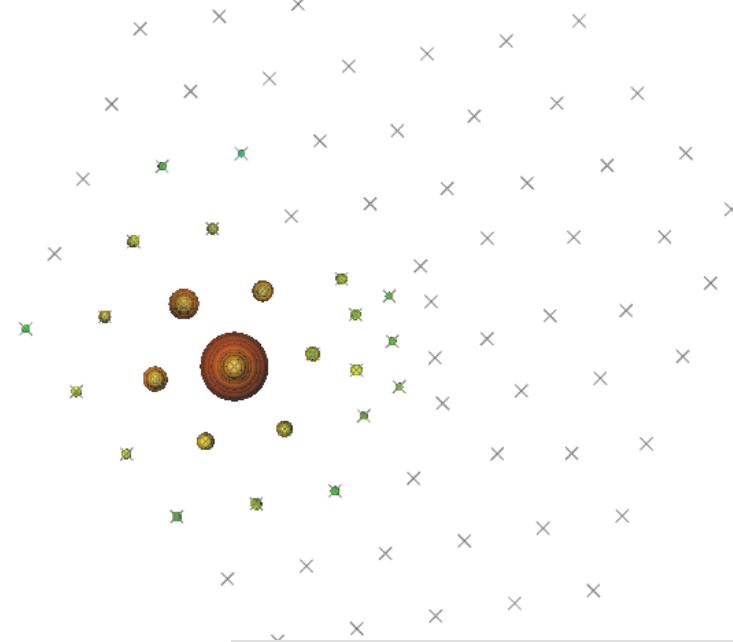
Limited by fluctuations in energy deposition.



Improving event reconstruction: cascades

Resolution:

$\approx \pm 15\%$ deposited energy
(incl. all sys. errors)
 $\approx 10^\circ$ angular resolution
(at energies $\gtrsim 100$ TeV)



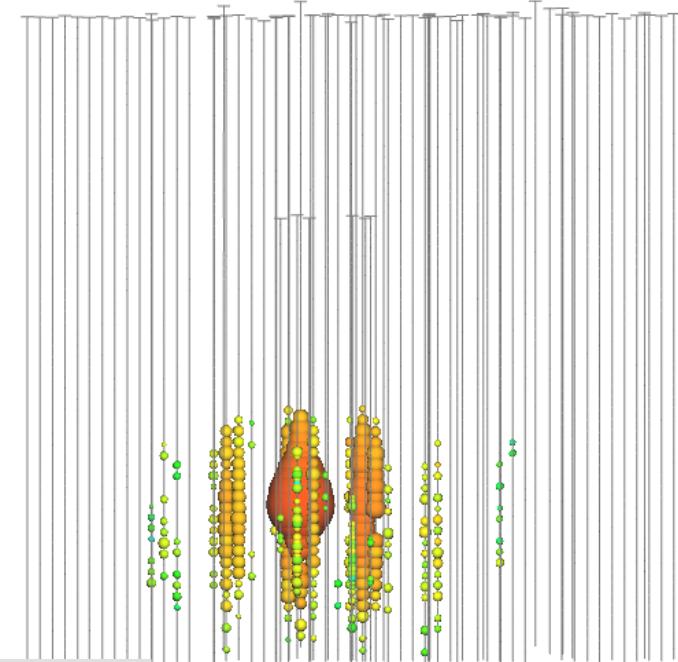
Example data event:

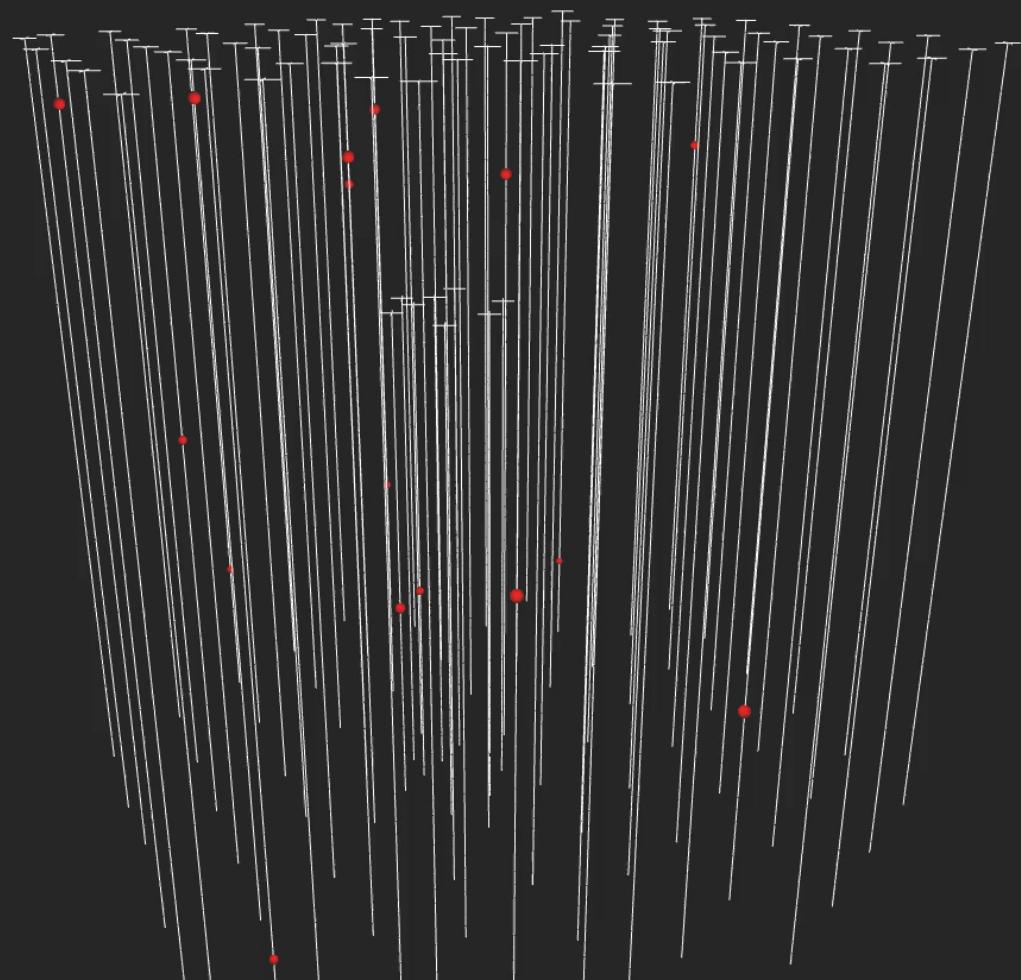
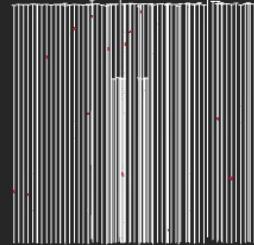
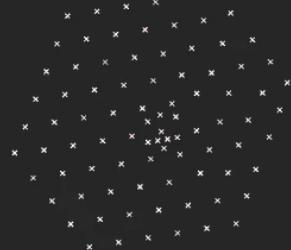
Reconstructed energy: 63 TeV (+7,-8 TeV)
Zenith angle: $\sim 54^\circ$

Charged Current: $\nu_e + N \rightarrow e + X$

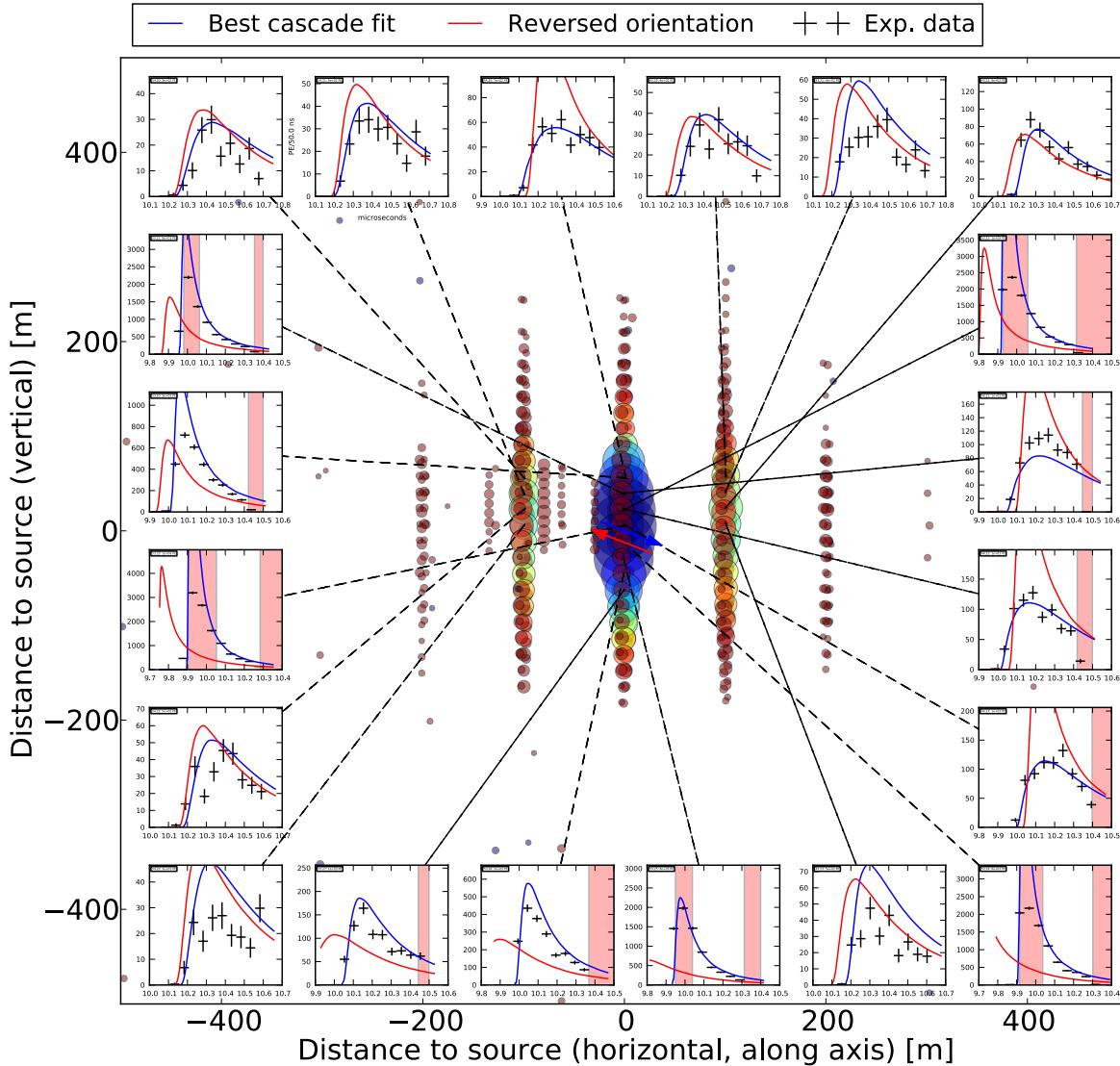
$\nu_\tau + N \rightarrow \tau + X$ (*Energy $< \sim$ few PeV*)

Neutral Current: $\nu_x + N \rightarrow \nu_x + X$





Observed neutrino event at $E=1.1 \times 10^6$ GeV



Shown is one event with best fit (blue) and forced reverse direction (red)

Event contains 354 waveforms and a total of > 90,000 photoelectrons

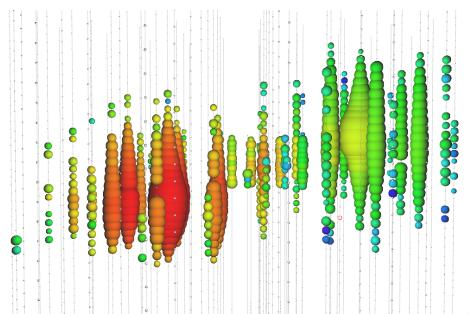
Widths of waveform related to direction of Cherenkov cone
 Preliminary pointing established (blue line).
 independent reconstruction algorithms agree
 Need to use most advanced ice models
 Integrated charge proportional to energy.
 Energy uncertainty: +15%/-13%

Tau neutrinos

Charged Current tau neutrino:

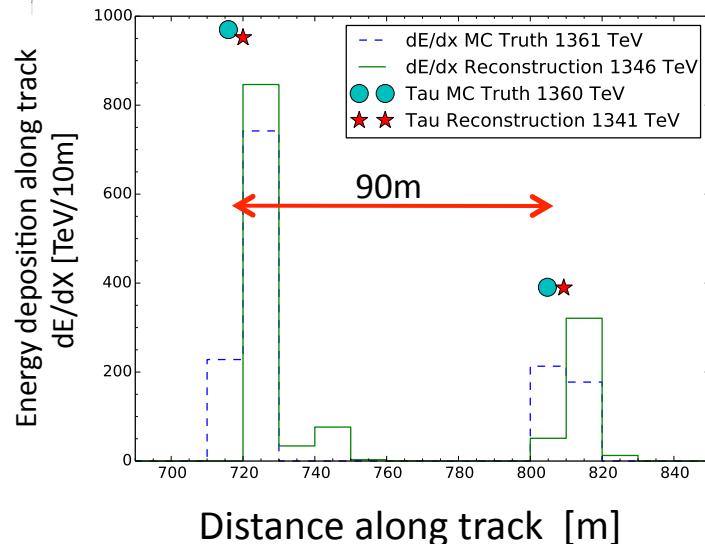
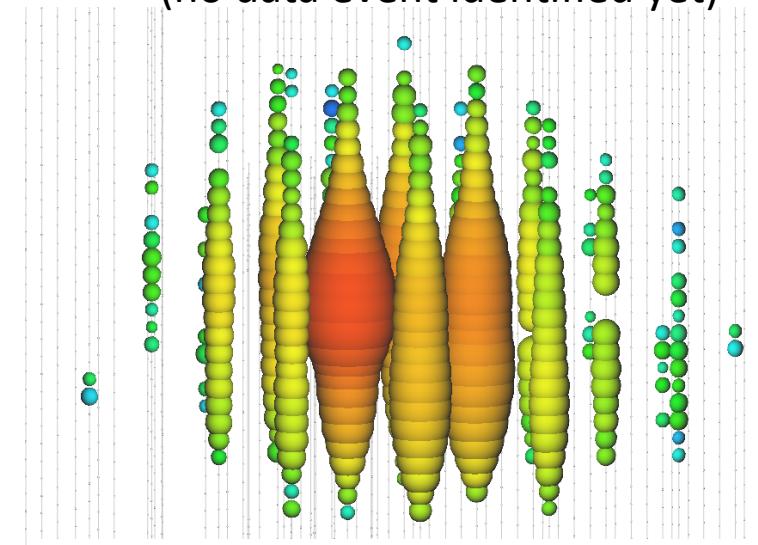
$$\nu_\tau + N \rightarrow \tau + X$$

Double-bang signature from decaying tau, $l_\tau = \gamma c t_\tau \sim 50 (E_\tau / \text{PeV}) \text{ m}$
Can identify double bang above $\sim \text{PeV}$
Lower energy id more limited possibilities.

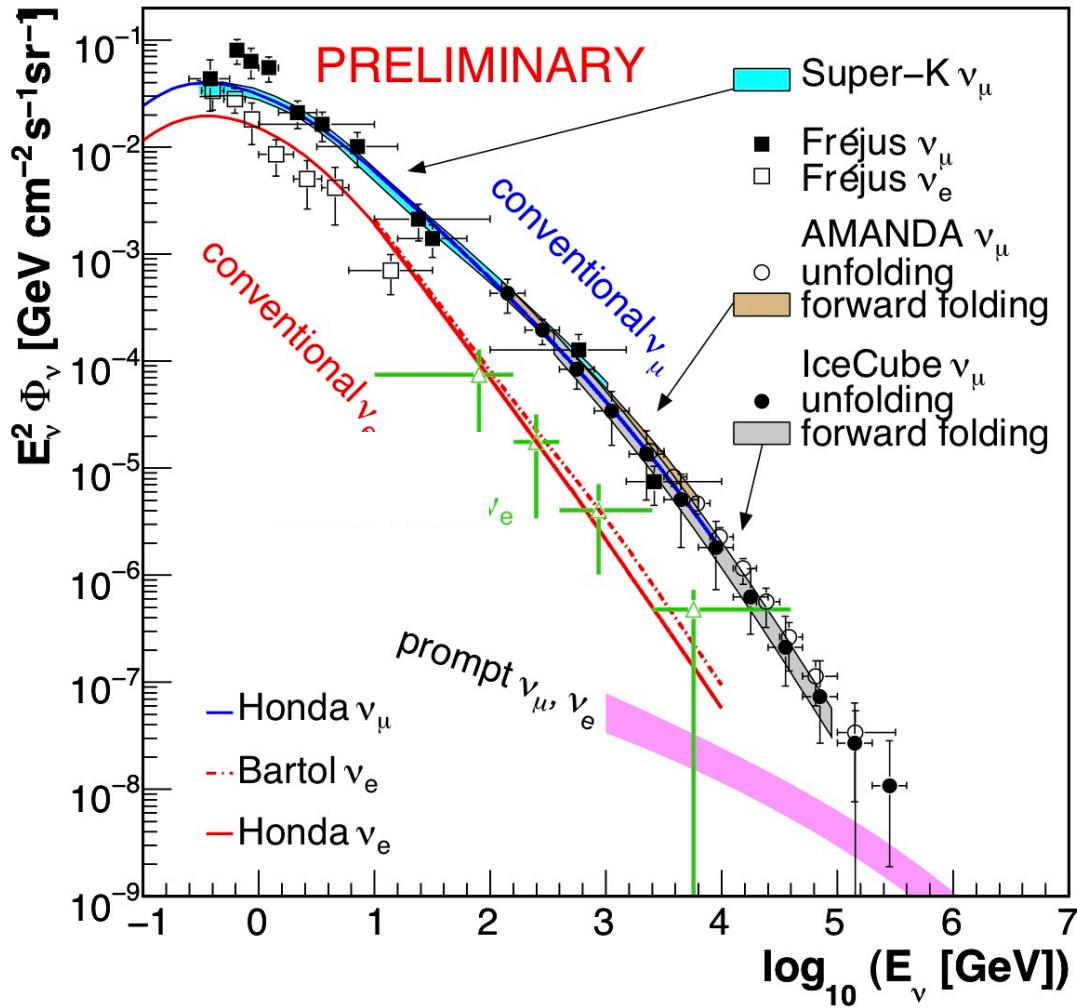


Event with longer decay length

Simulated event: 1.36 PeV
 (no data event identified yet)



Atmospheric Neutrinos



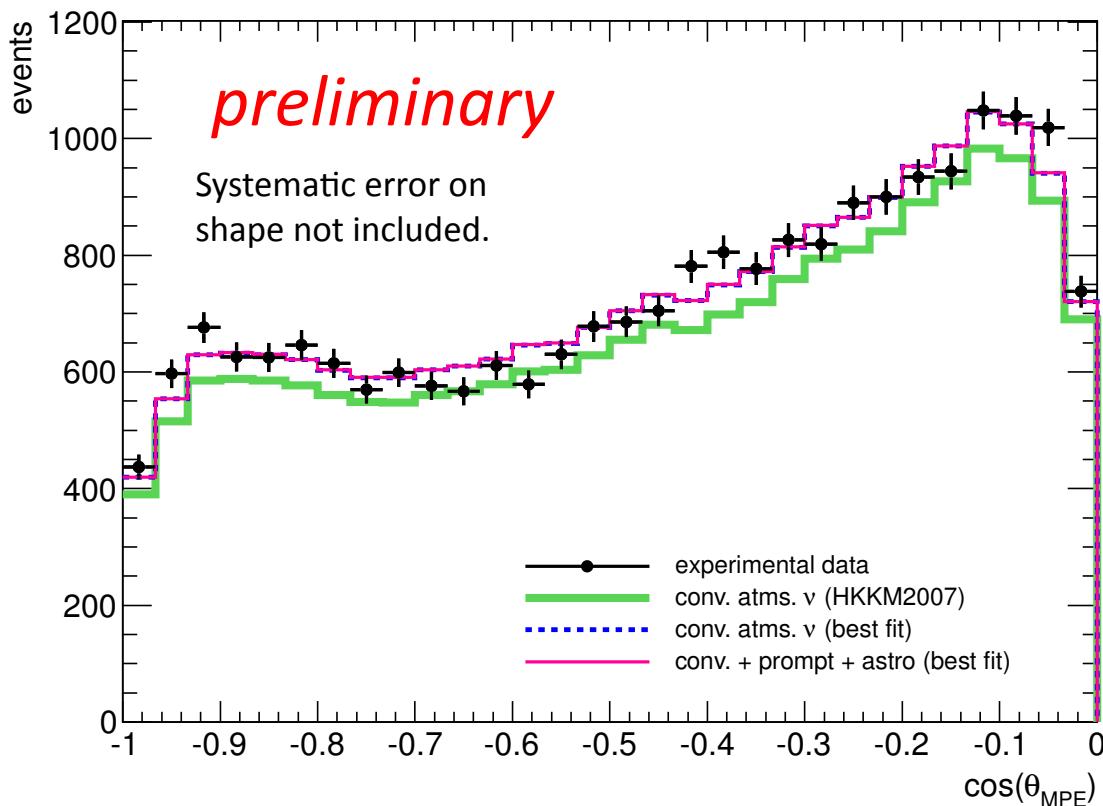
Very large neutrino sample: > 50k events per year of purity,

Muon neutrinos into 100's of TeV

Now also Electron neutrinos up to TeV energies arXiv:1212.4760

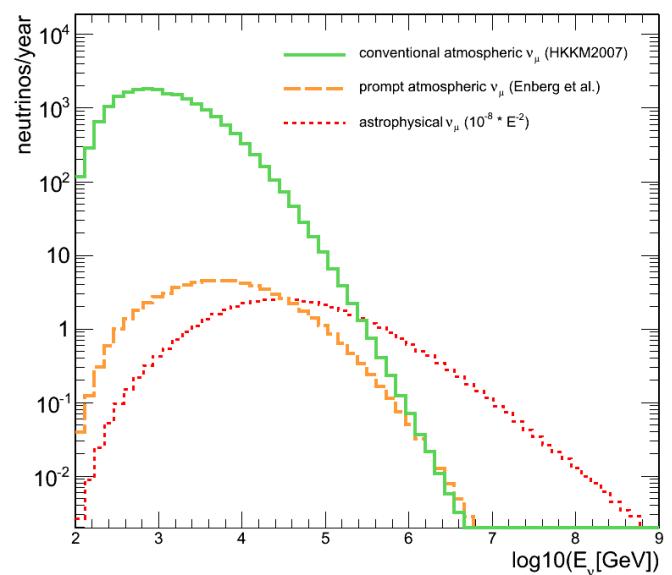
Approaching the ability to test prompt models

IC 59- zenith angle distribution

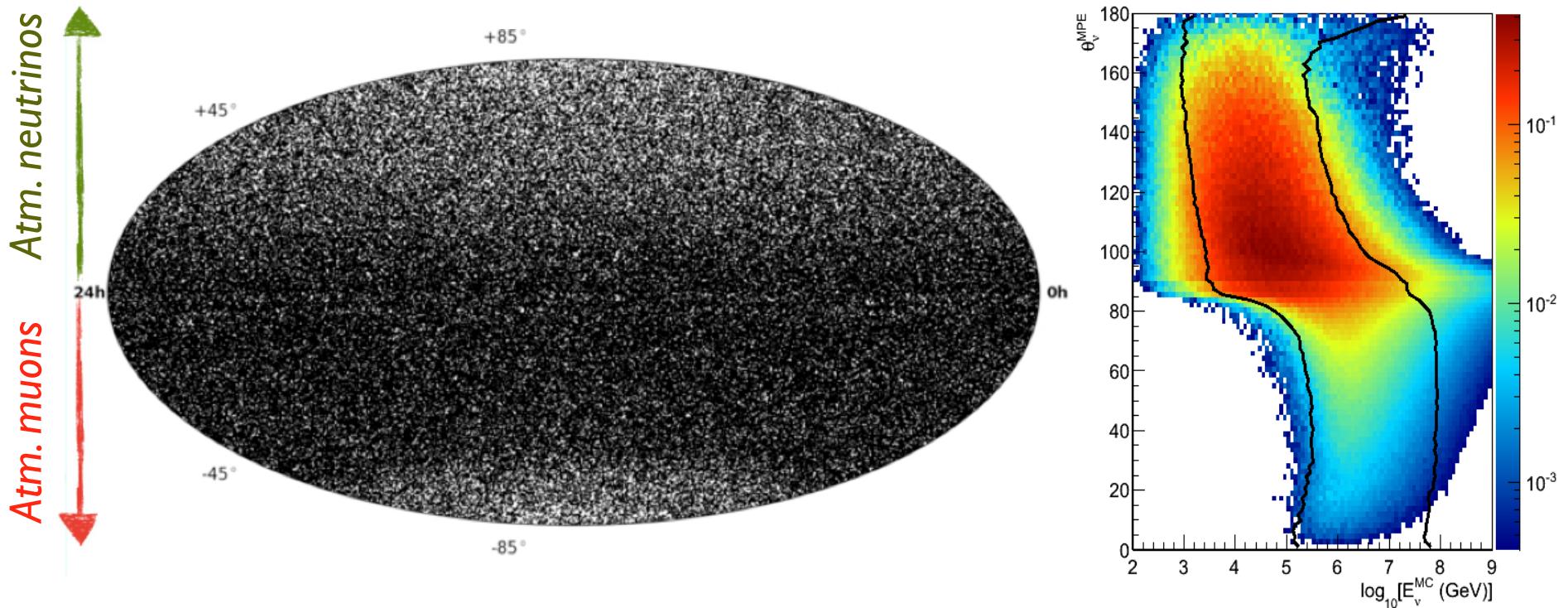


To date, IceCube has accumulated $\sim 250k$ atmospheric neutrinos between 0.3 and 100 TeV

Agreement of data with atmospheric simulation.
Analysis under way for atmospheric neutrino spectrum.
Searches for physics beyond standard model:
- Lorentz invariance
- **Sterile neutrinos**



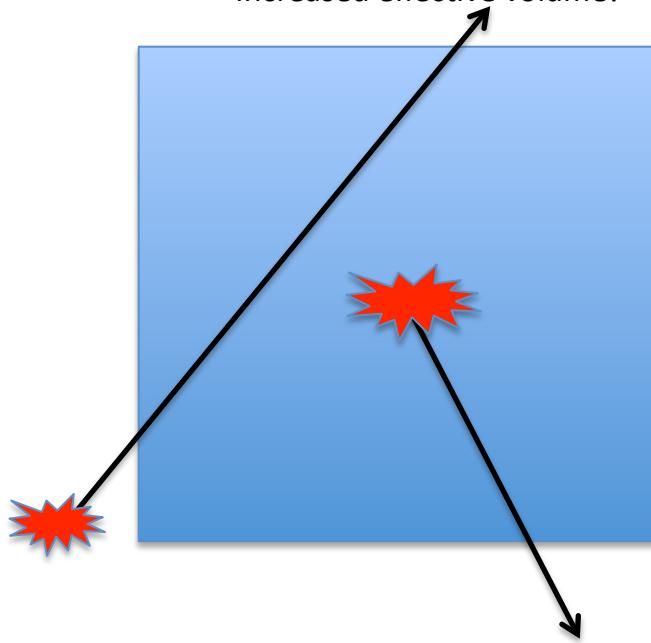
Point Source Search



- Total events (IC40+IC59+IC79+IC86-1): 394000 events
178k neutrino candidates in North, 216k atmospheric muons in South
- Livetime: 1371 days

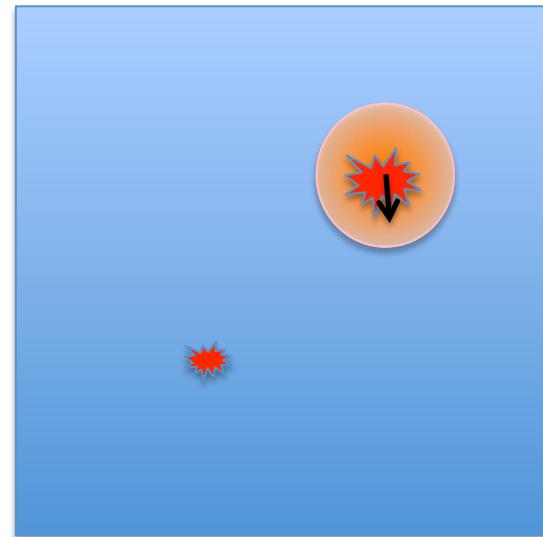
Event types – search strategies

- **Throughgoing muons –**
 - the workhorse for neutrino astronomy, good angular resolution
 - Vertex can be far outside the detector. Increased effective volume!



- Starting tracks: downgoing neutrino astronomy (reject background of throughgoing cosmic ray muons AND possibly atmospheric neutrinos)

- **Cascade events:**
 - ν_e, ν_τ and neutral current
 - High energy resolution (fully active calorimeter, all energy gets deposited in the detection volume)
 - Angular reconstruction above $\sim 50\text{TeV}$



IceCube diffuse neutrino searches

Look for neutrino events at high energy, above the rapidly falling atmospheric neutrino spectrum.

1. ν_μ signal: for upward going tracks ($\text{zenith} > 85^\circ$)
 - IC 40 (40 strings) published [Phys. Rev. D 84, 082001 (2011) [arXiv: 1104.5187v5](#)], → upper limit
 - Results from IC 59 search: → upper limit (2sigma tension to zero astrophys.)
2. Cascade search
 - Cascade only events, contained, some tension to zero astrophysical
3. Extremely high energy events, downgoing events at energies above downgoing muons background (PeV – EeV)
4. Starting track results, Events with contained vertex
~100 TeV to PeV

[Start with 3 and 4 and put other results in perspective](#)

Search for Cosmogenic or GZK Neutrinos

- looking for the brightest events

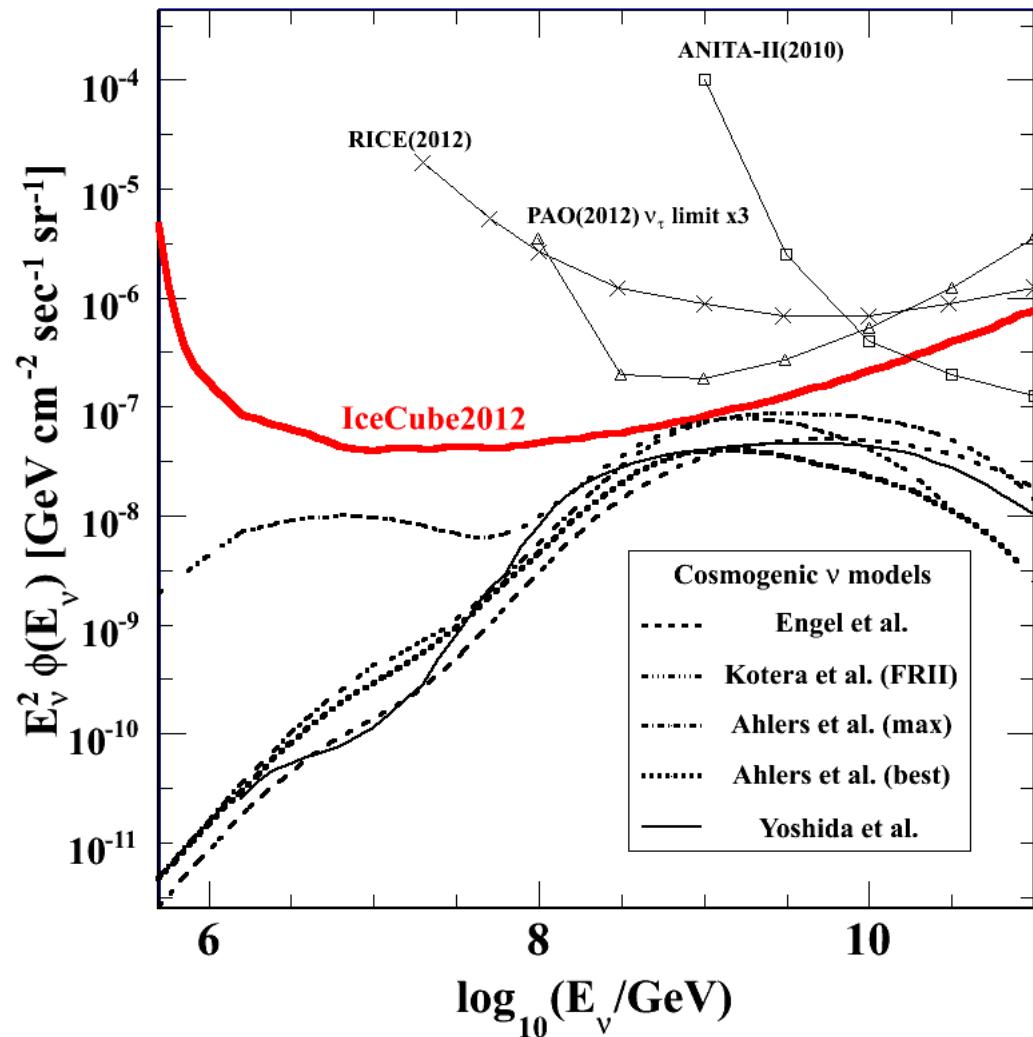
→ Talk by Aya Ishihara

First observation of PeV-energy neutrinos with IceCube
Phys. Rev. Lett. 111, 021103 (2013)
arXiv:1304.5356

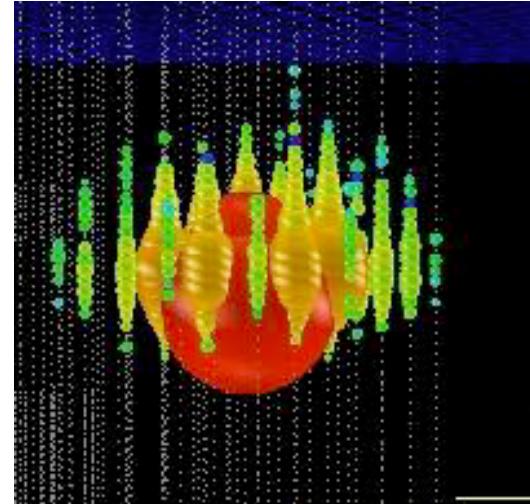
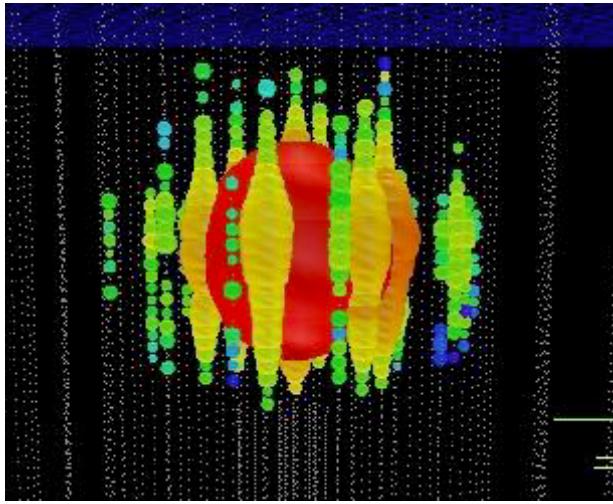
Data from 2010-2012: ~ 2 years of livetime with 90% and 100% complete detector.

Analysis looks for very bright events, energy range PeV – EeV, where no atmospheric background is expected.

Two very interesting events were found at ~1 PeV.



Two events found at PeV energies



	Event 1	Event 2
date (GMT)	August 8, 2011	January 3, 2012
Number of Photoelectrons	7.0×10^4	9.6×10^4
number of recorded DOMs	312	354
reconstructed energy	1.04+-0.16 PeV	1.14+-0.17 PeV
reconstructed <i>z</i> vertex	121.8 m	24.6 m

Error on vertex position: ~ 5m

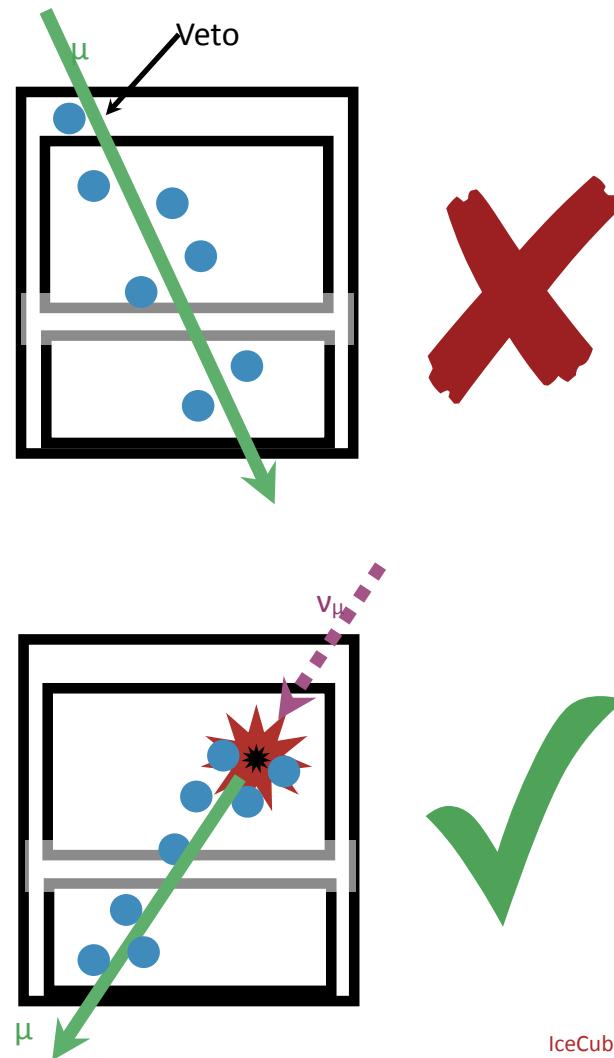
Significance above background: 2.8 sigma

Follow-up Analysis

Specifically designed to find these contained events

Analysis of dataset taken from May 2010 to May 2012 (662 days of livetime)

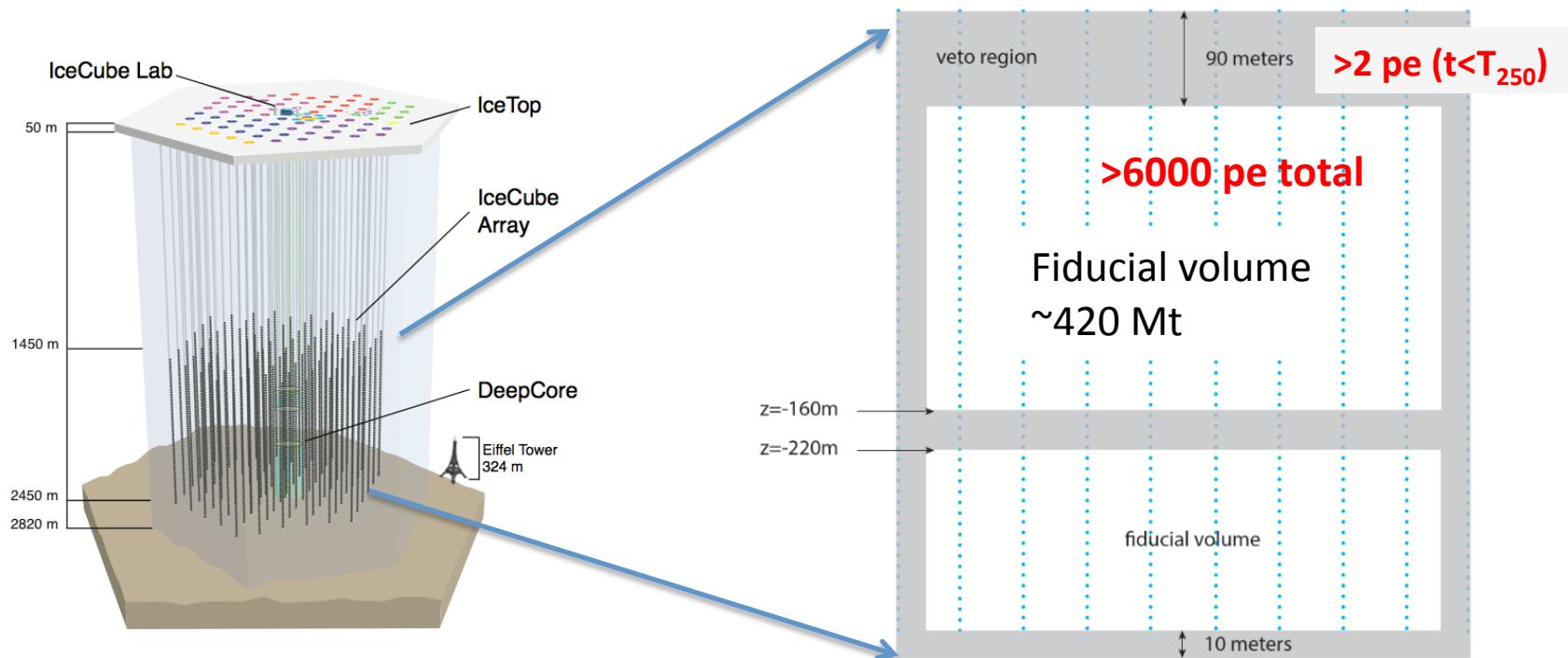
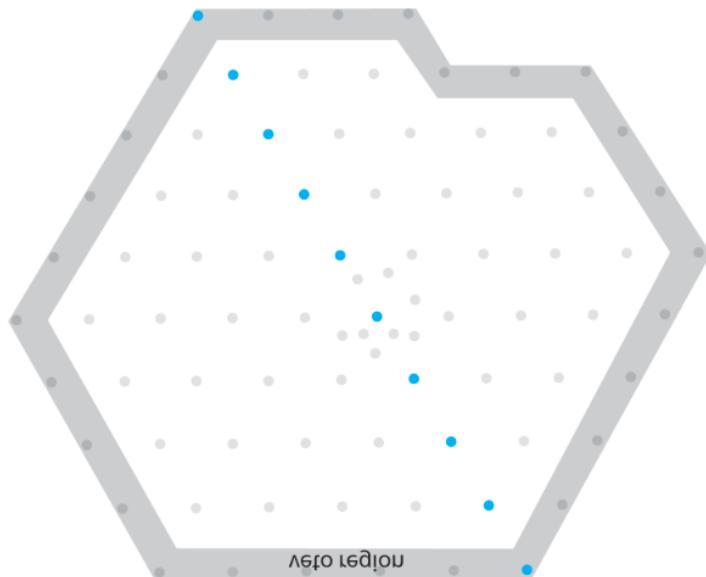
- Search for events with contained vertex – **starting tracks** - at high energies (cut: $Q_{\text{tot}} > 6000$)
- Sensitive to all flavors at energies above 60 TeV
- Three times as sensitive at 1 PeV
- 400 Mton effective fiducial mass
- Veto of downgoing atmospheric muons AND neutrinos
- Estimate background from data



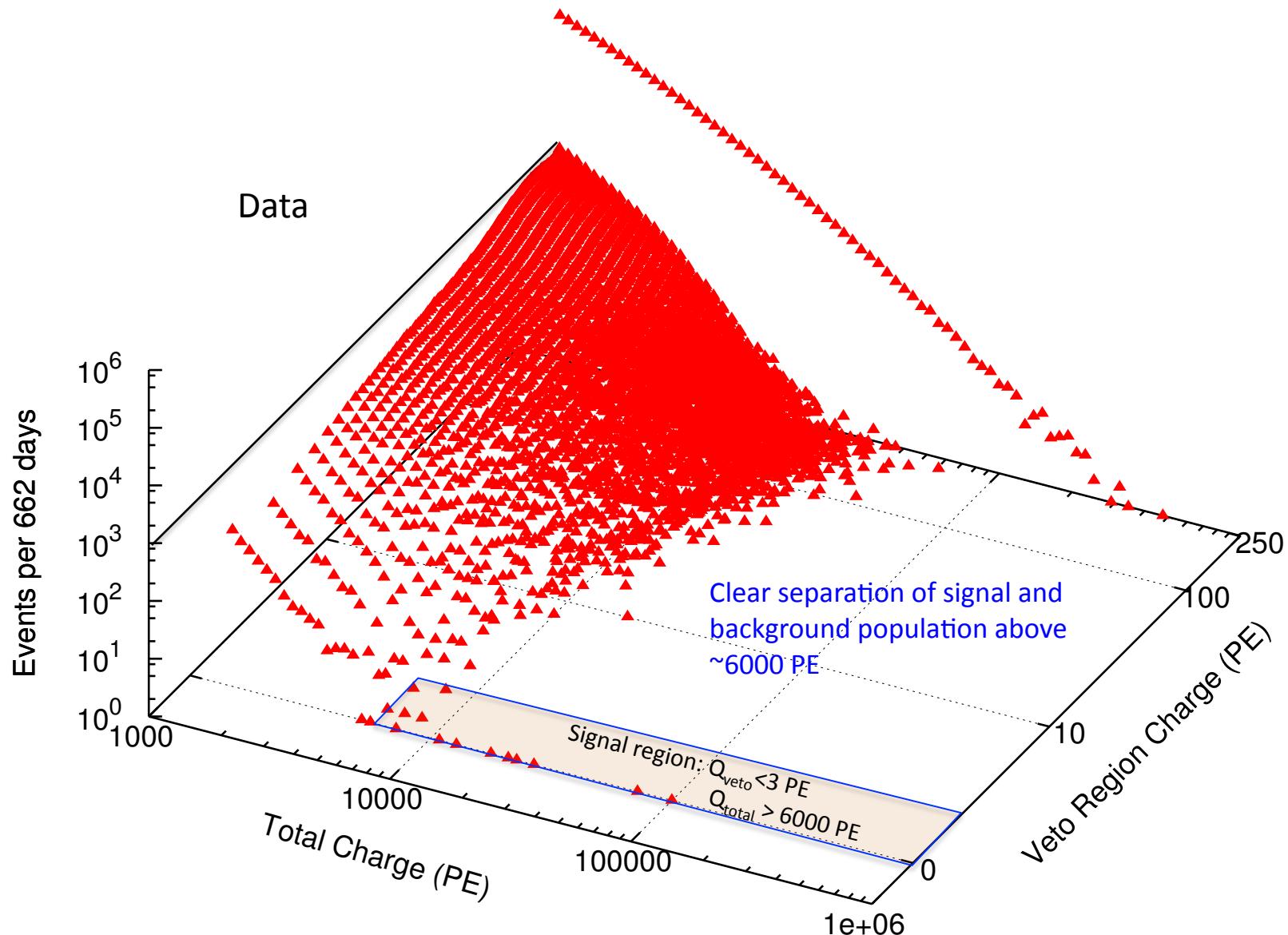
Veto region

The PMT signals of all PMTs
in the veto region are treated as Veto signals:
~2400 DOMs
Contained vertex events: “First light is in fiducial
region”

Amongst the first 250 photoelectrons of an event,
not more than 3.0 photoelectrons are allowed in
the veto region.



Event selection: Compare total charge with charge in veto region

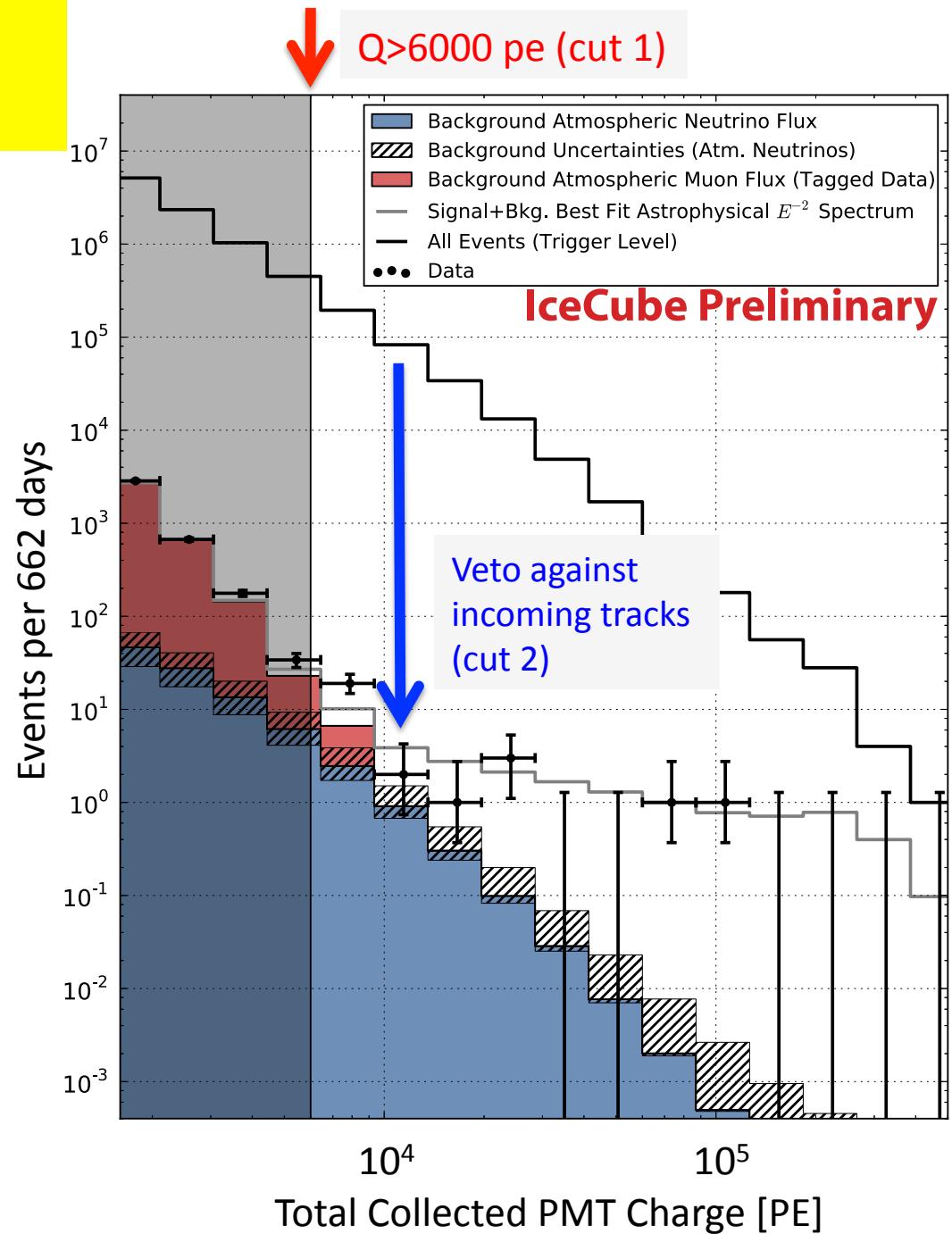


Energy distribution using total deposited charge.

After cut on total charge and application of veto:
28 events

(2 of them the original 2 PeV events reported earlier)

- Fits well to tagged background estimate from atmospheric muon data (red) below charge threshold ($Q_{\text{tot}} > 6000$)
- Hatched region includes uncertainties from conventional and charm atmospheric neutrino flux (blue)

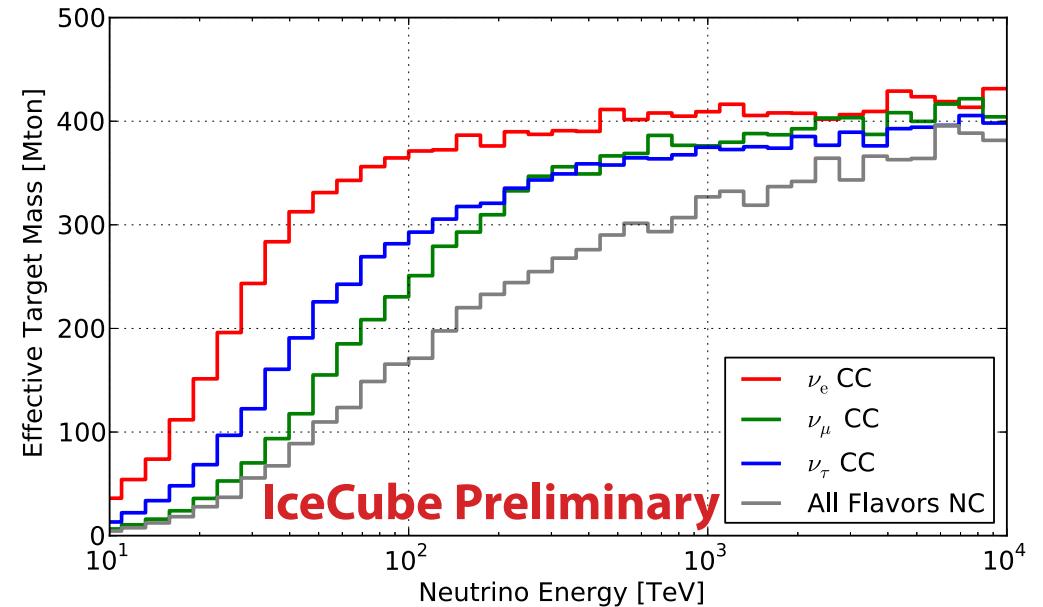


Effective volume and effective area

Effective volume (mass)

Fully efficient above 100 TeV for CC electron neutrinos

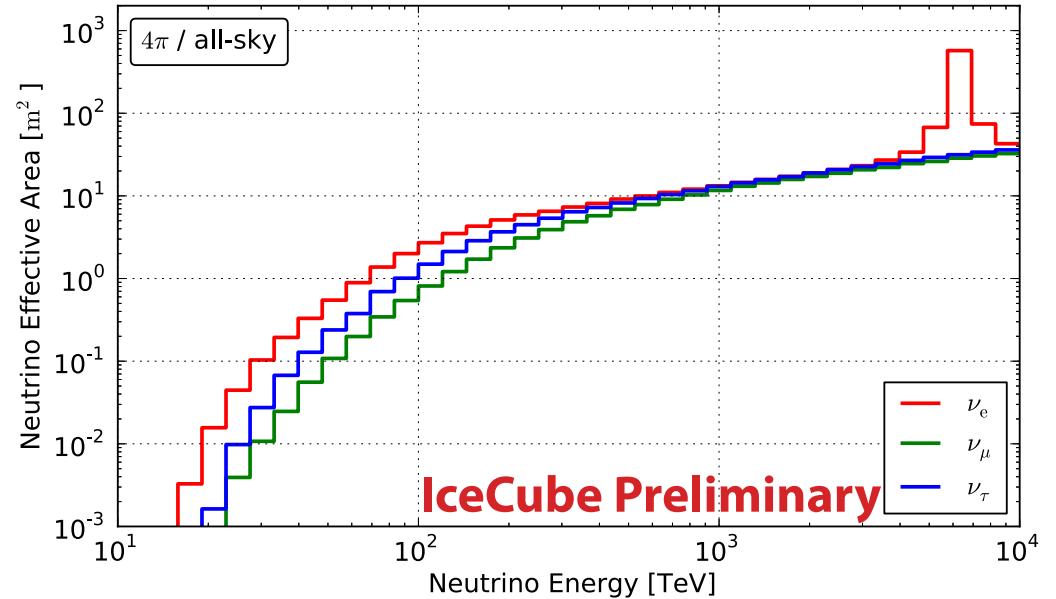
About 400 Mton effective target mass



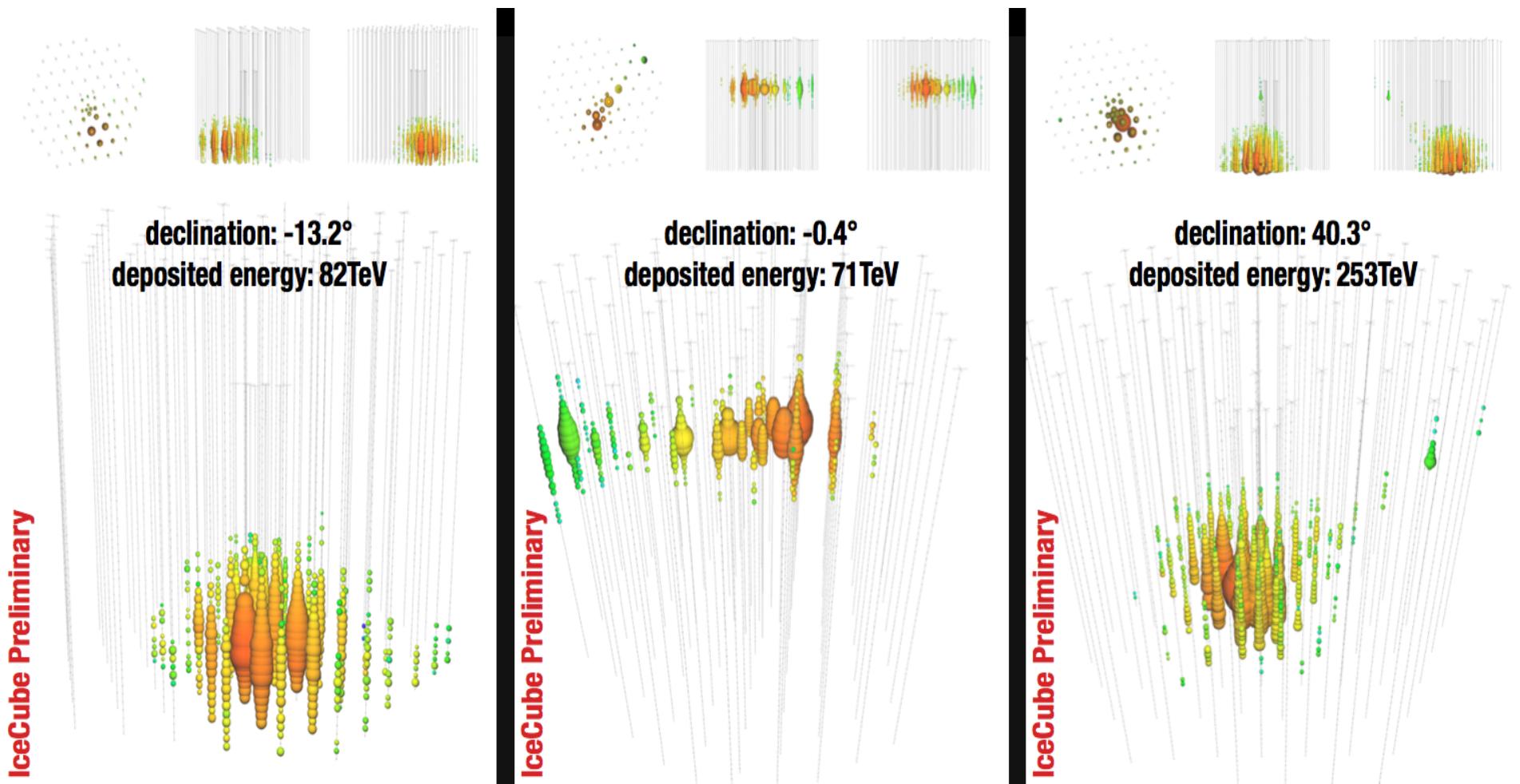
Neutrino effective area

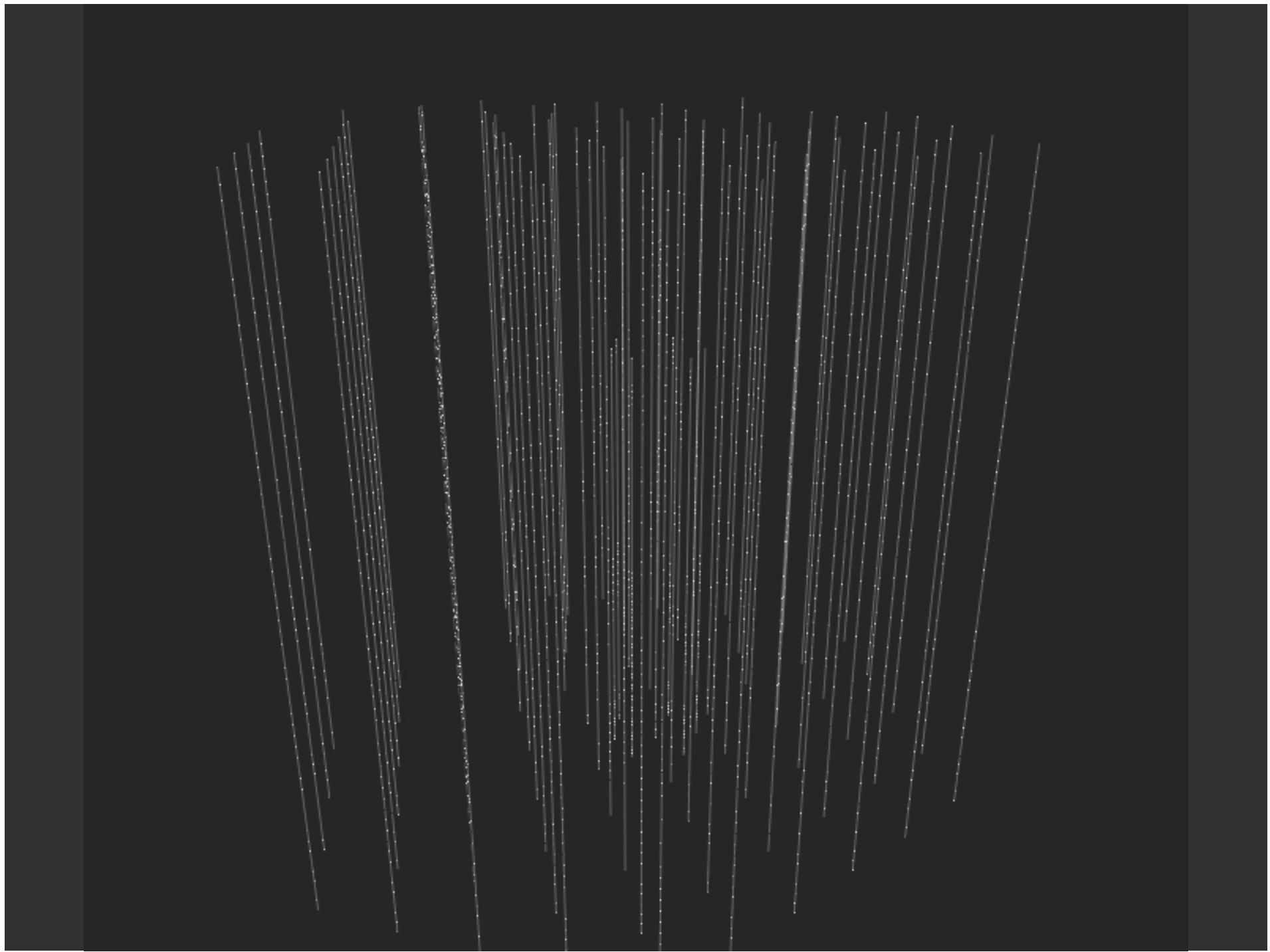
Energy threshold for muons higher as the muon will carry away energy.

Cascades deposit nearly all energy.



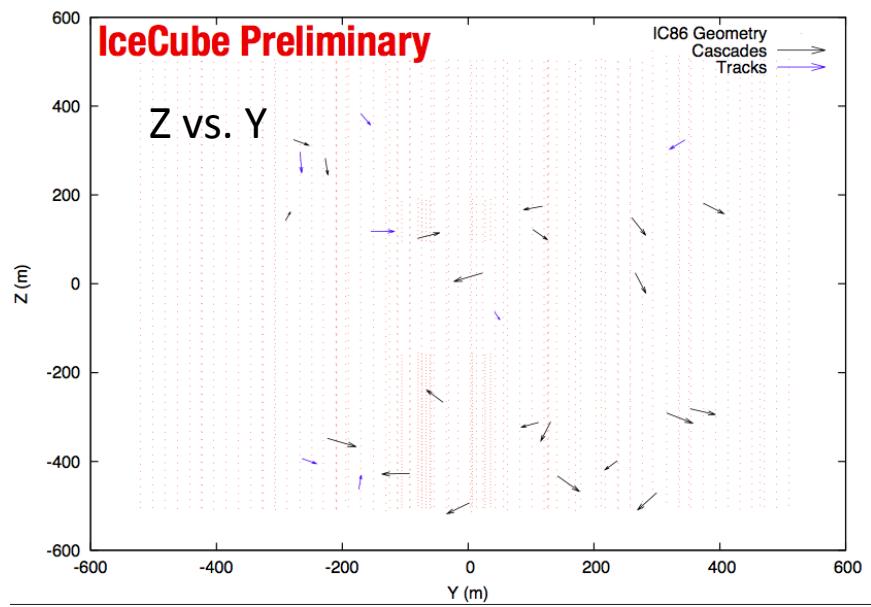
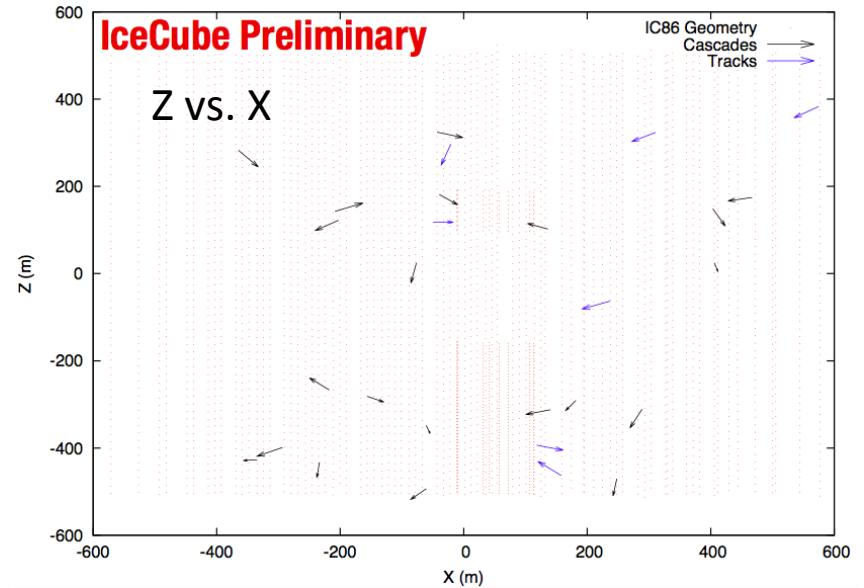
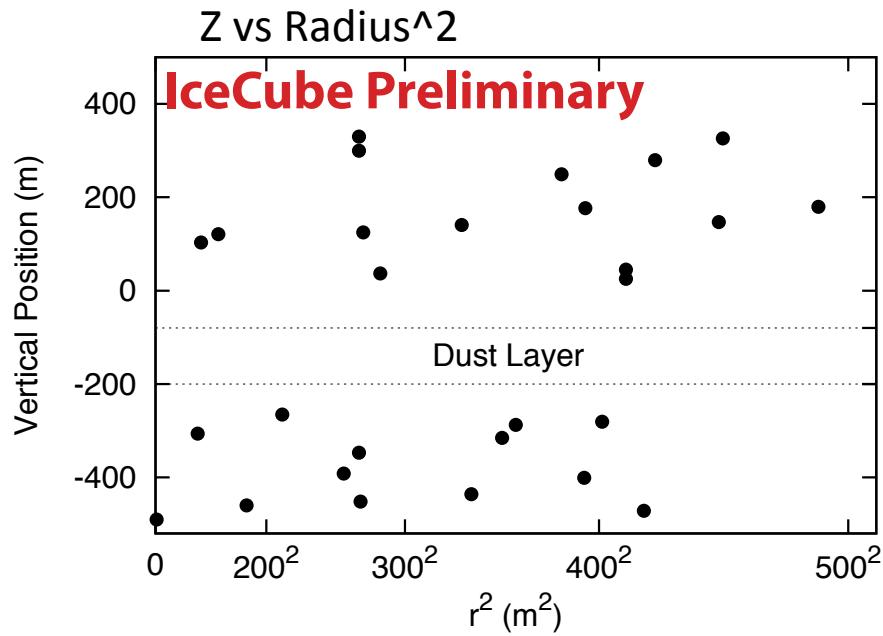
Examples of events found



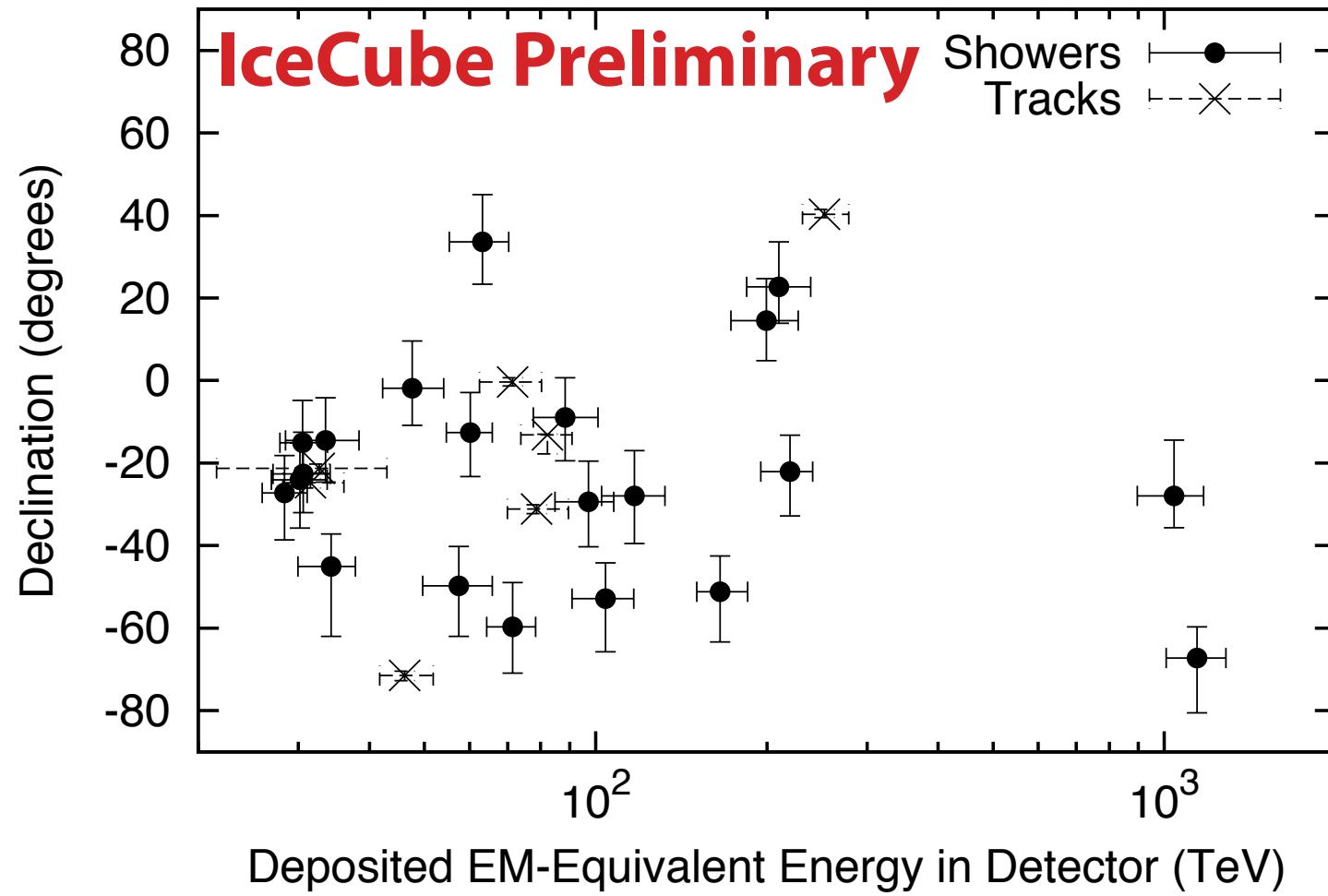


Vertex and directions of events in detector volume

→ Events are uniformly distributed in volume



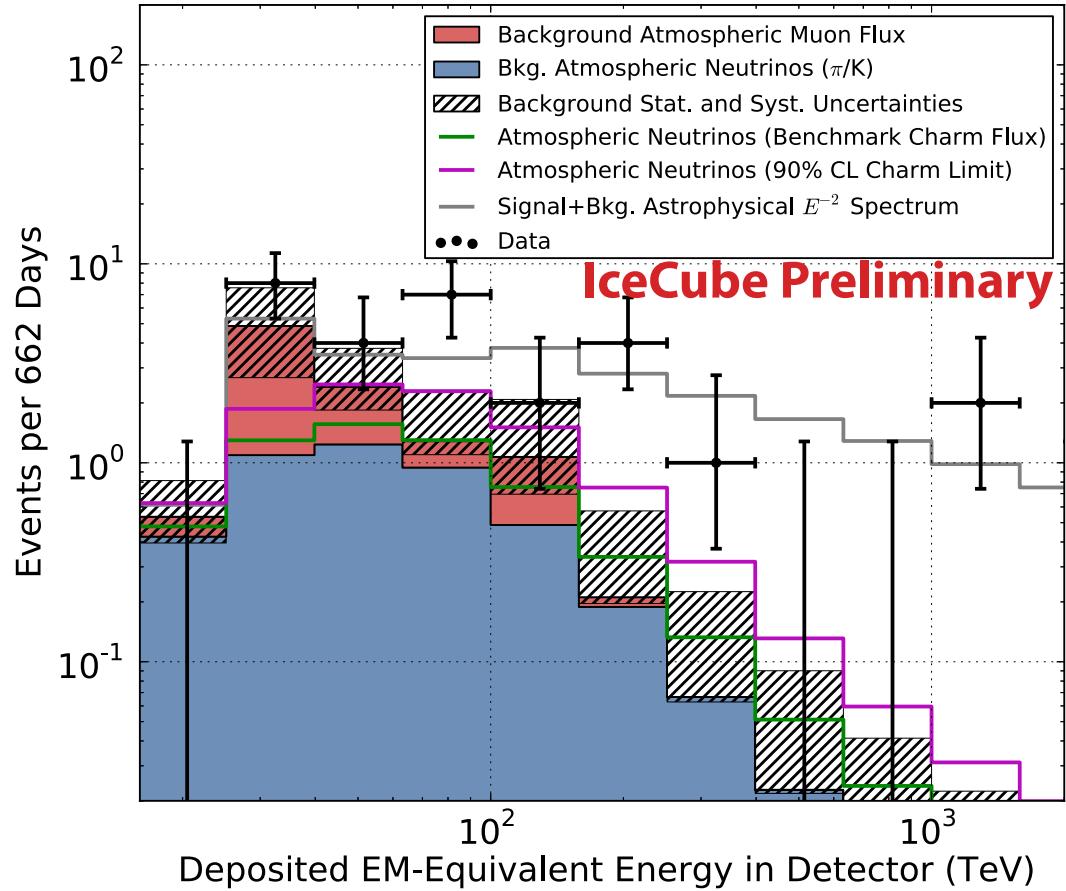
Declination vs energy



Most events in Southern hemisphere (downgoing).

Energy distribution

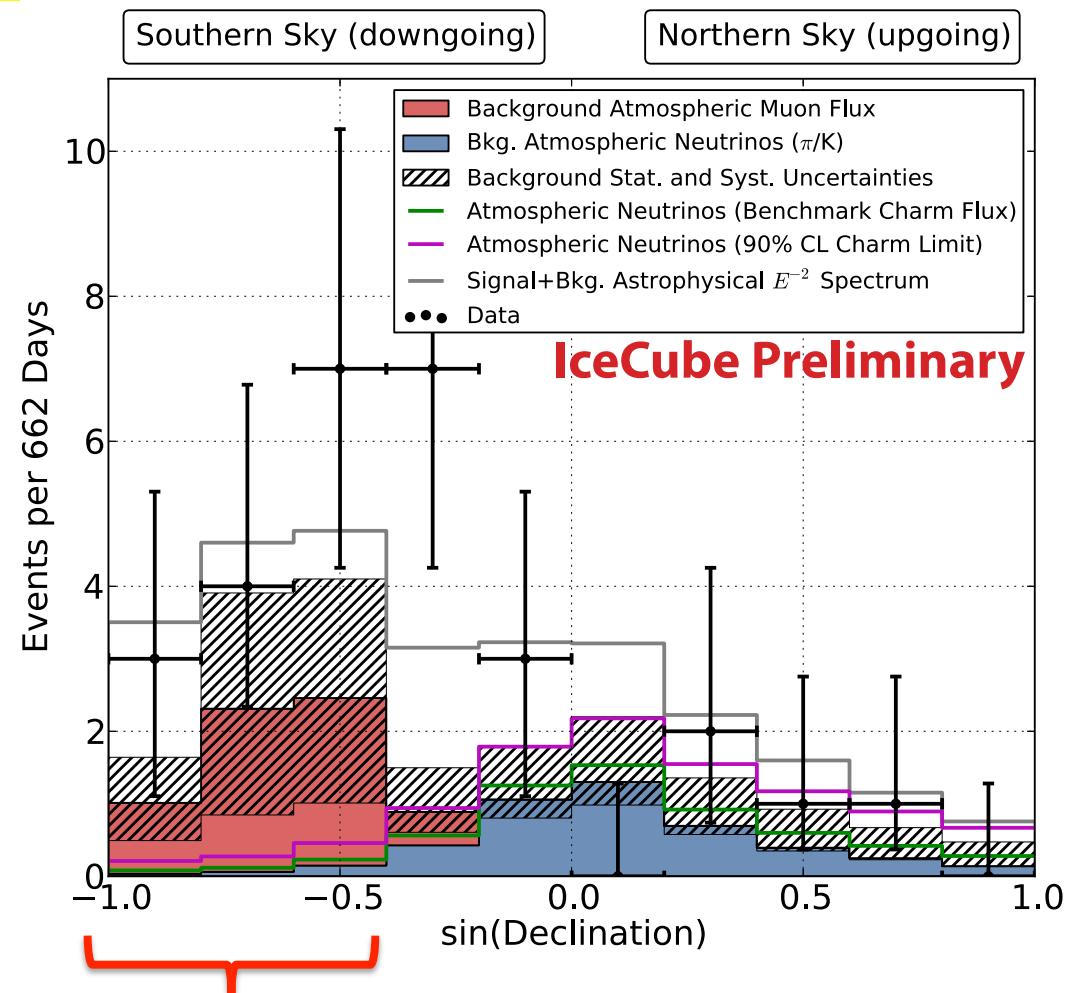
- Harder than any expected atmospheric background
- Merges well into background at low energies
- Potential cutoff at about 2-5 PeV
 - at 1.6 (+1.5-0.4) PeV when fitting a hard cutoff
- Best fit (normalized to single flavor):
 $1.2 \pm 0.4 \times 10^{-8} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$
- Inconsistent at 4 σ level with standard atmospheric backgrounds, astrophysical origin most compatible explanation, but no clear picture.



*Note that the energy scale is the deposited energy.
Muons will carry away some energy.
Electron and tau neutrinos deposit all energy.*

Zenith angle, declination distribution

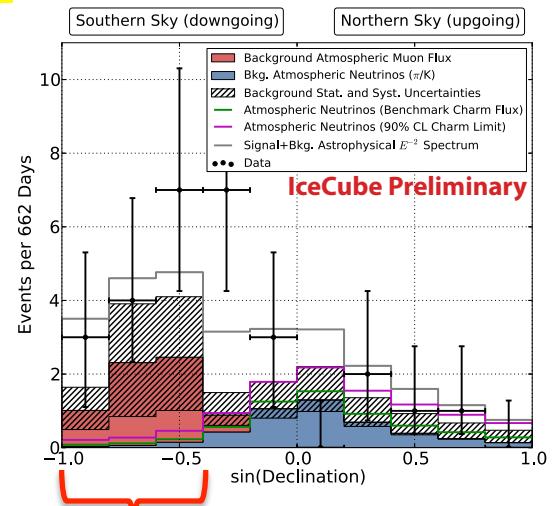
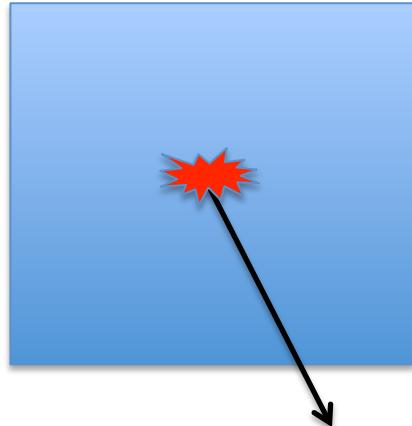
- Angular distribution makes atmospheric explanation very hard.
- Compatible with isotropic flux
- Absorption matters for upgoing events at higher energies



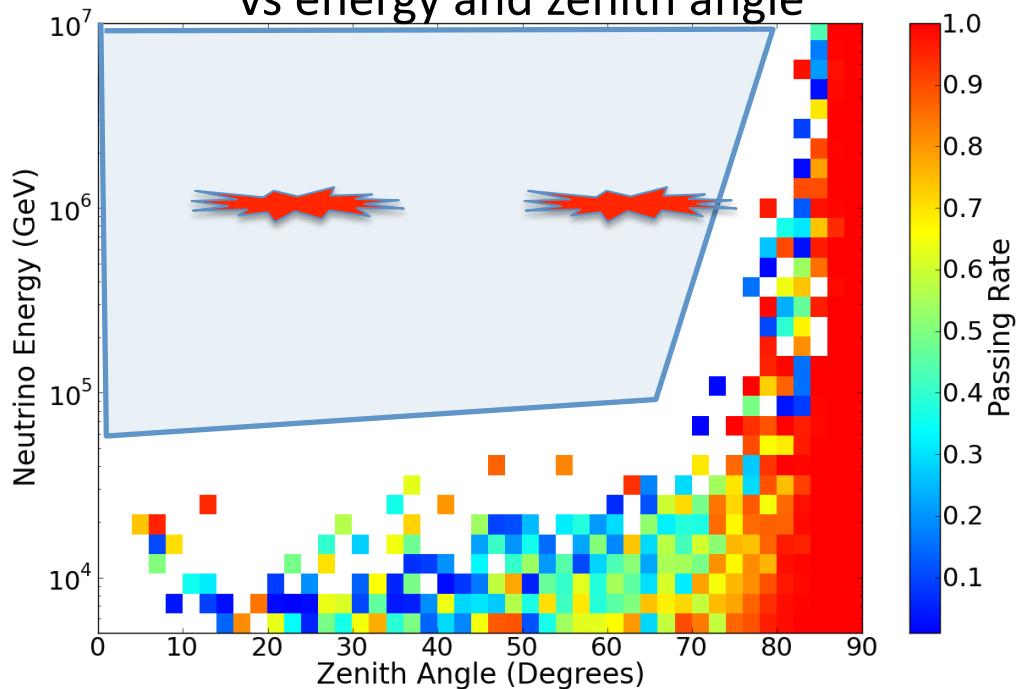
Very low background of downgoing atmospheric neutrinos due to veto.

Background free neutrino astronomy?

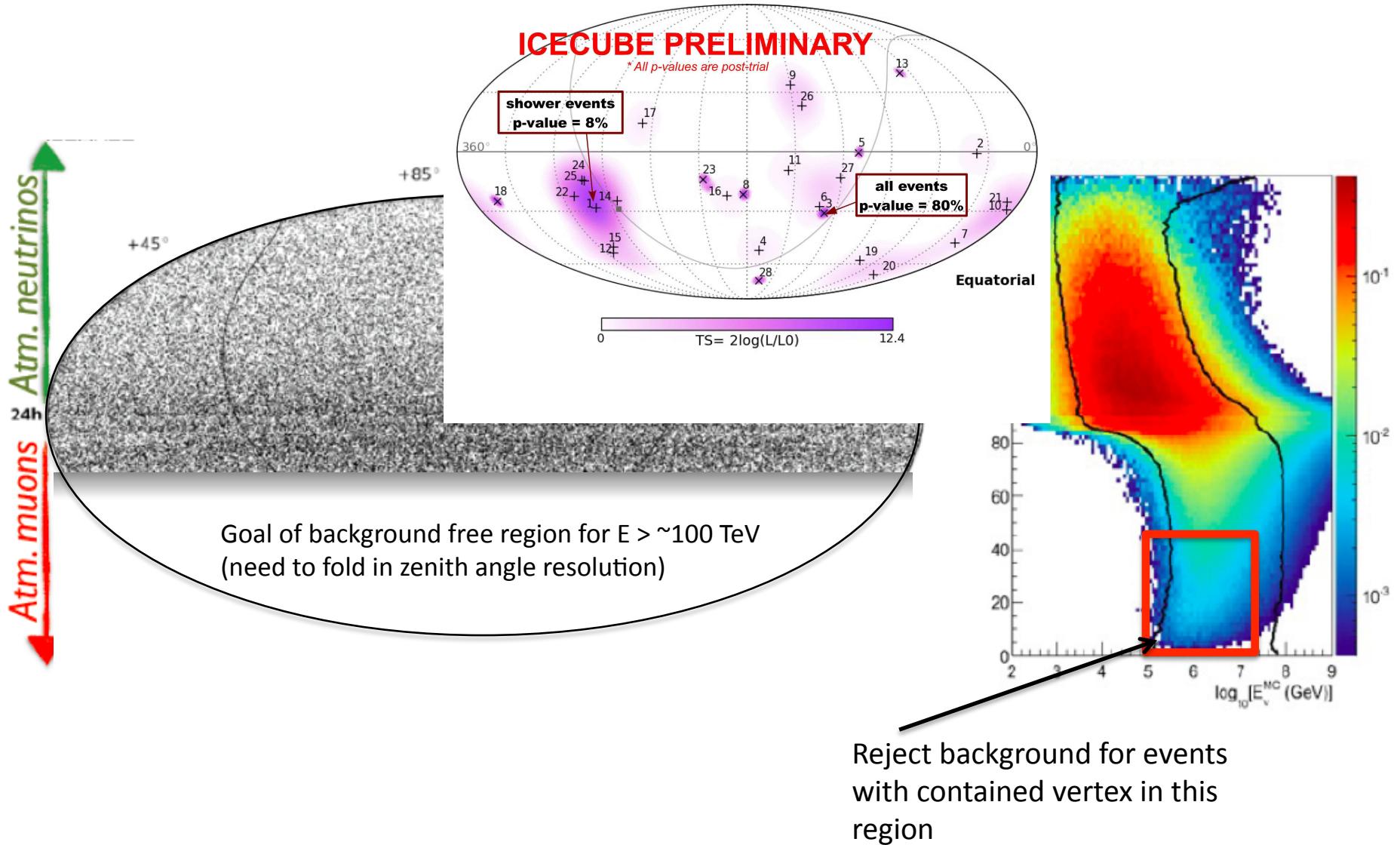
- Reject some of higher energy atmospheric neutrino background
 - Downgoing energetic neutrinos with
 - $E > 100 \text{ TeV}$
 - zenith angle less than 50°
- will likely be accompanied by muons from the same air shower.
- A starting neutrino in that region unlikely to be atmospheric.



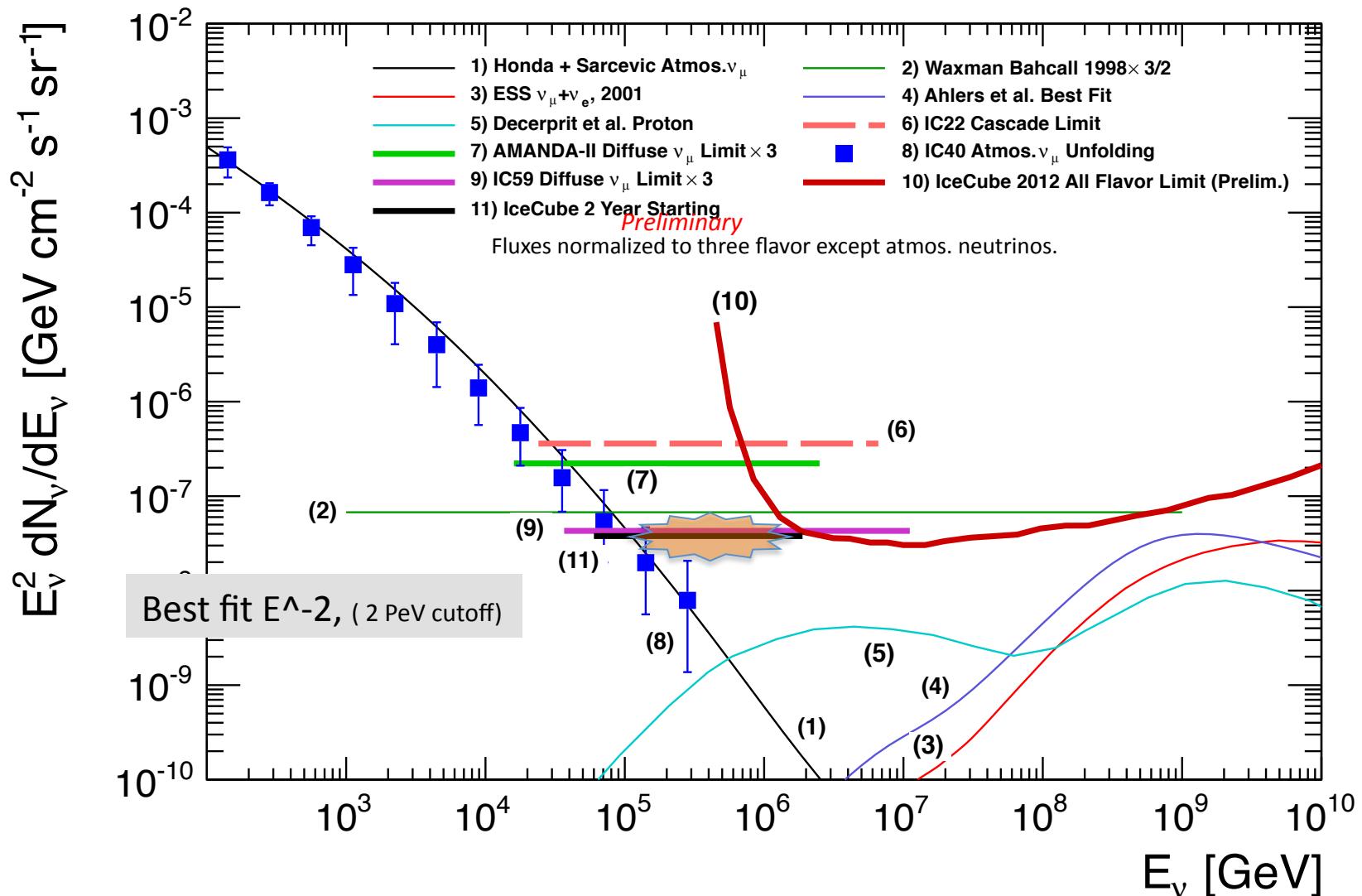
Passing rate
vs energy and zenith angle

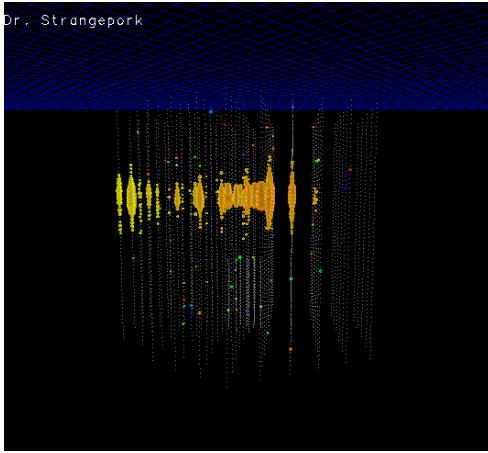


Strategy to remove all background:
 - neutrino telescope going up-side down at $E > 100\text{TeV}$



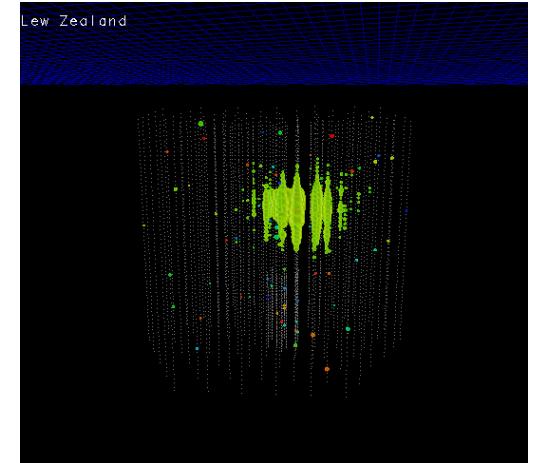
Neutrino fluxes – Limits, sensitivities of detectors





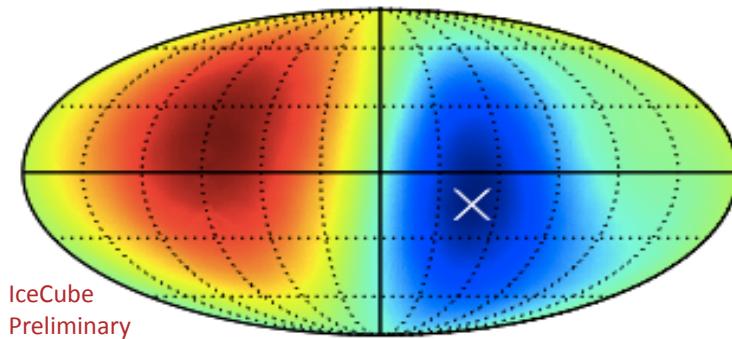
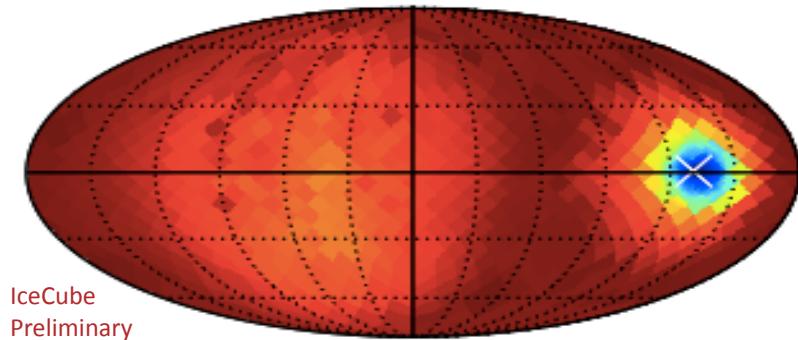
Event Reconstruction

Generic full-sky likelihood scan for each event



Muon neutrino: $\sim 1^\circ$ resolution

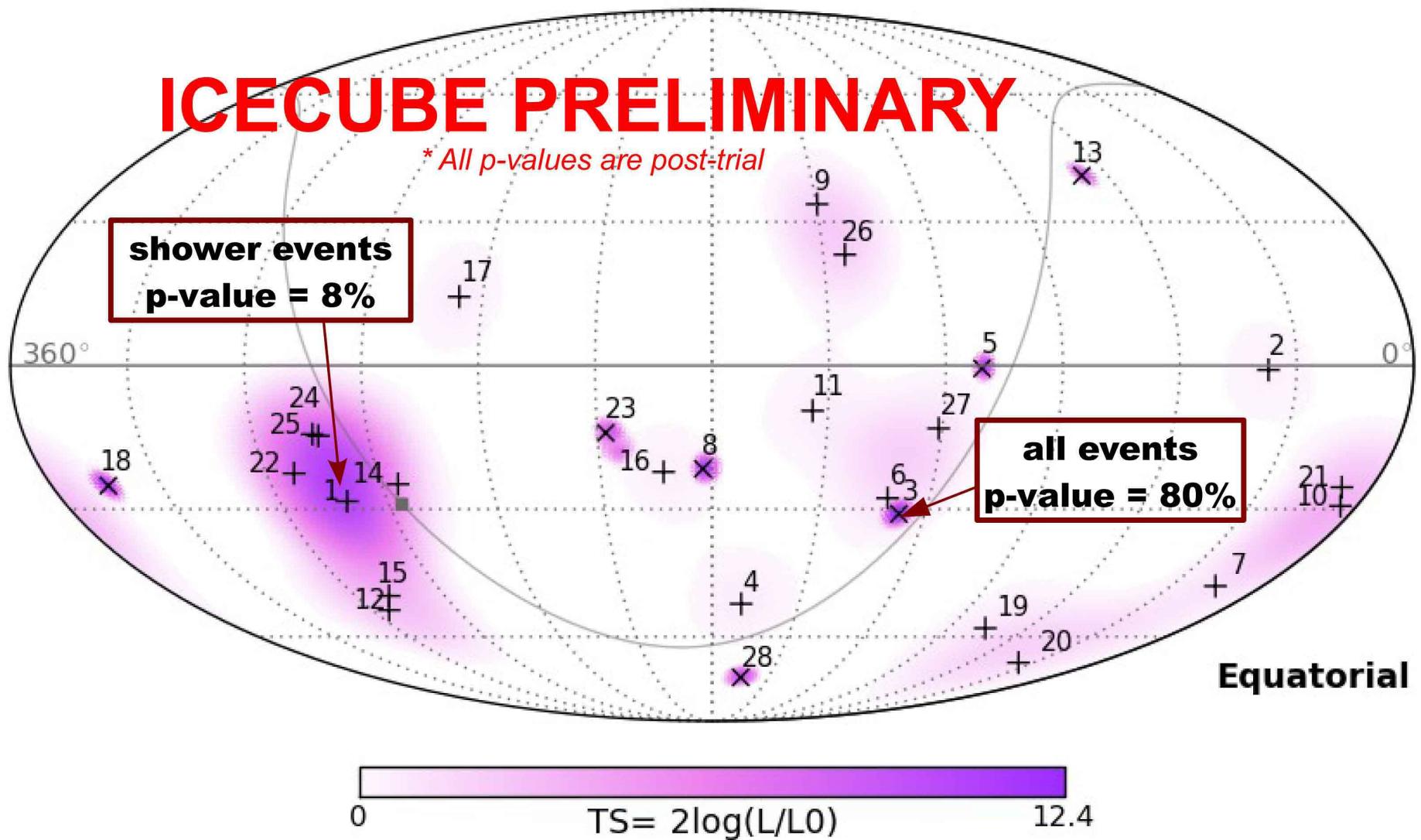
Cascade (e, tau, NC) event: $\sim 10^\circ$ resolution



- ▶ Result: direction with uncertainty and estimate for deposited energy
- ▶ Use density maps of reconstructed events to construct zenith angle probabilities and skymaps

ICECUBE PRELIMINARY

* All p-values are post-trial



→ No significant clustering of events that would be indicator of a point source.

Other analysis channels

- Need all channels to understand what we are seeing.
 - Point sources
 - Diffuse nu-mu channel
 - Above ~ 1 PeV: a factor of 2 in eff. area should be possible (w/o veto)
 - Reconstruction based search will improve efficiency of cascade searches

See talks by:

Aya Ishihara, GZK neutrino search

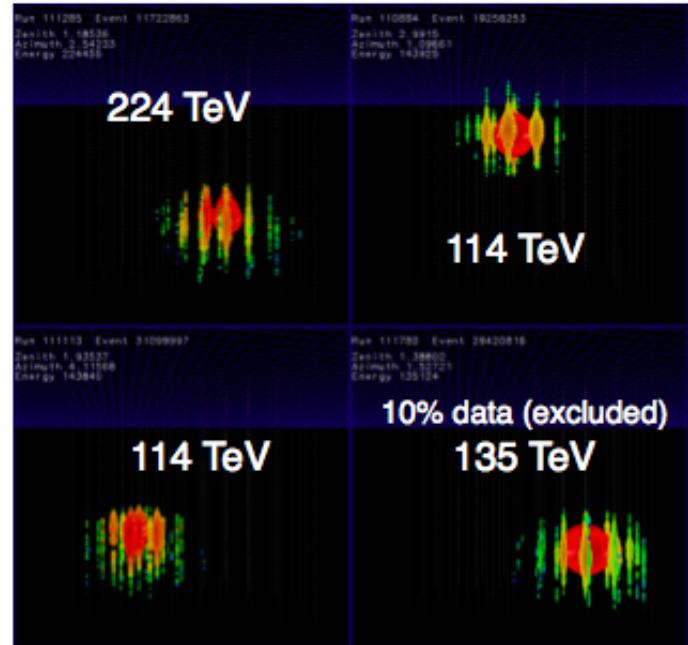
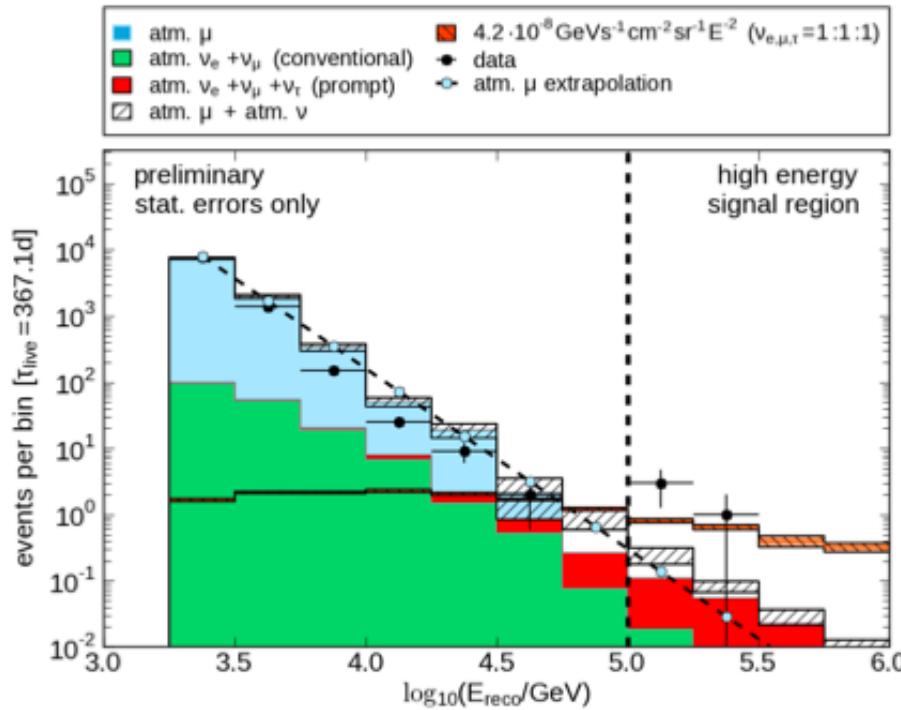
Ignacio Taboada: GRB

J. Feintzeig

A few comments on cascades and diffuse nu-mu.

Cascade searches

Example: IC40 search for neutrino induced cascades



Tension with atmospheric background only assumption also on cascade channel:

Observed 3 events with:

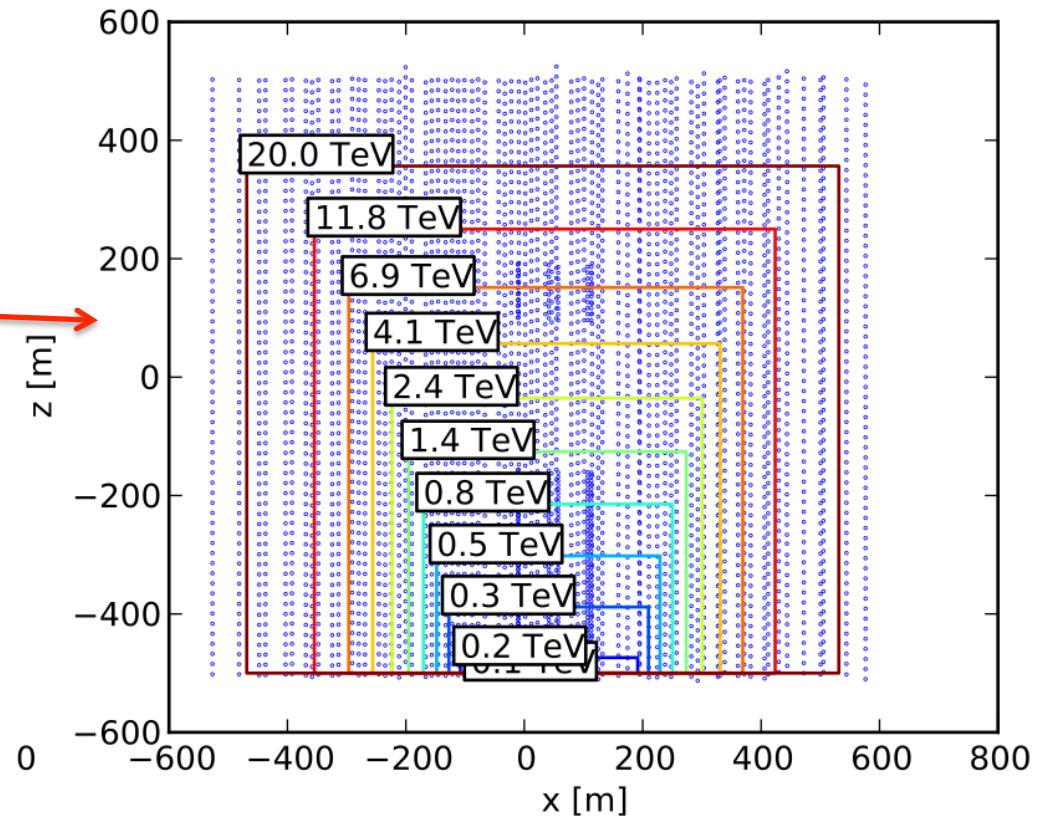
- 2.75σ excess over atm. μ
- 2.4σ excess over atm. μ and ν (conventional + prompt)

Bg estimate from extrapolation, statistical uncertainties only

→ Talk by J. Kiryluk

Future of veto strategies for contained vertex analyses

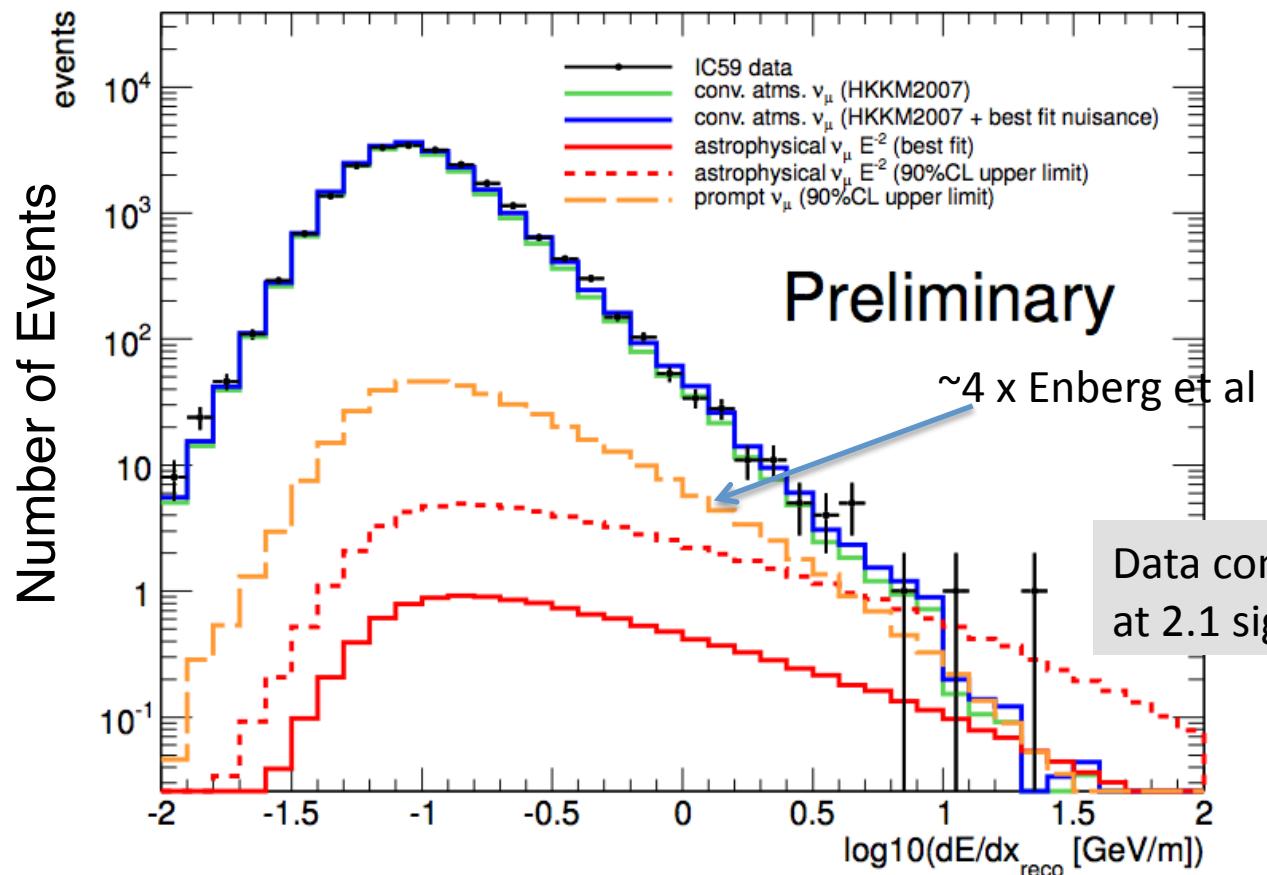
- Veto application for contained vertex are becoming powerful at
 - high energies (>100 TeV)
 - Low energies 10 – 100 GeV (Deep Core)
- Goal: close gap!
- Also revisiting ideas for surface veto extensions of IceTop (simple ice tanks, air Cherenkov detectors)?



Preliminary estimates for energy dependent contained cascade Searches based on veto techniques.

IC 59 diffuse ν_μ flux

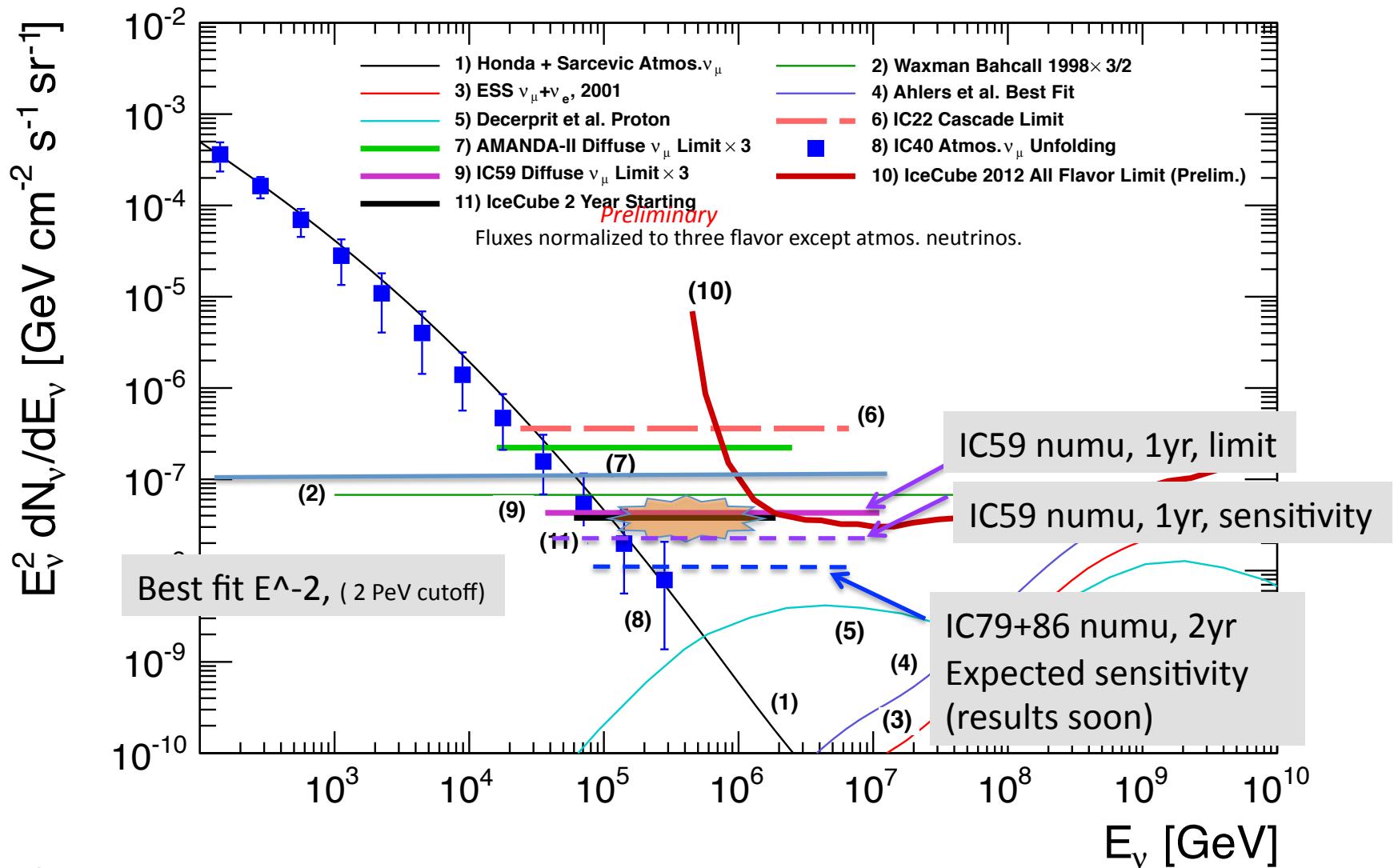
IC59 detector
May 2009 – May 2010



arXiv:1302.0127

Data from 2009-2010: 348 days of livetime with ~75% complete detector
Analysis looks for deviation from the expected atmospheric neutrino flux

How do the searches for a diffuse muon neutrino flux fit in?



Low energies, 1 – 100 GeV, DeepCore, PINGU ...

IceCube Energy scale:
 10^{12} – 10^{18} eV

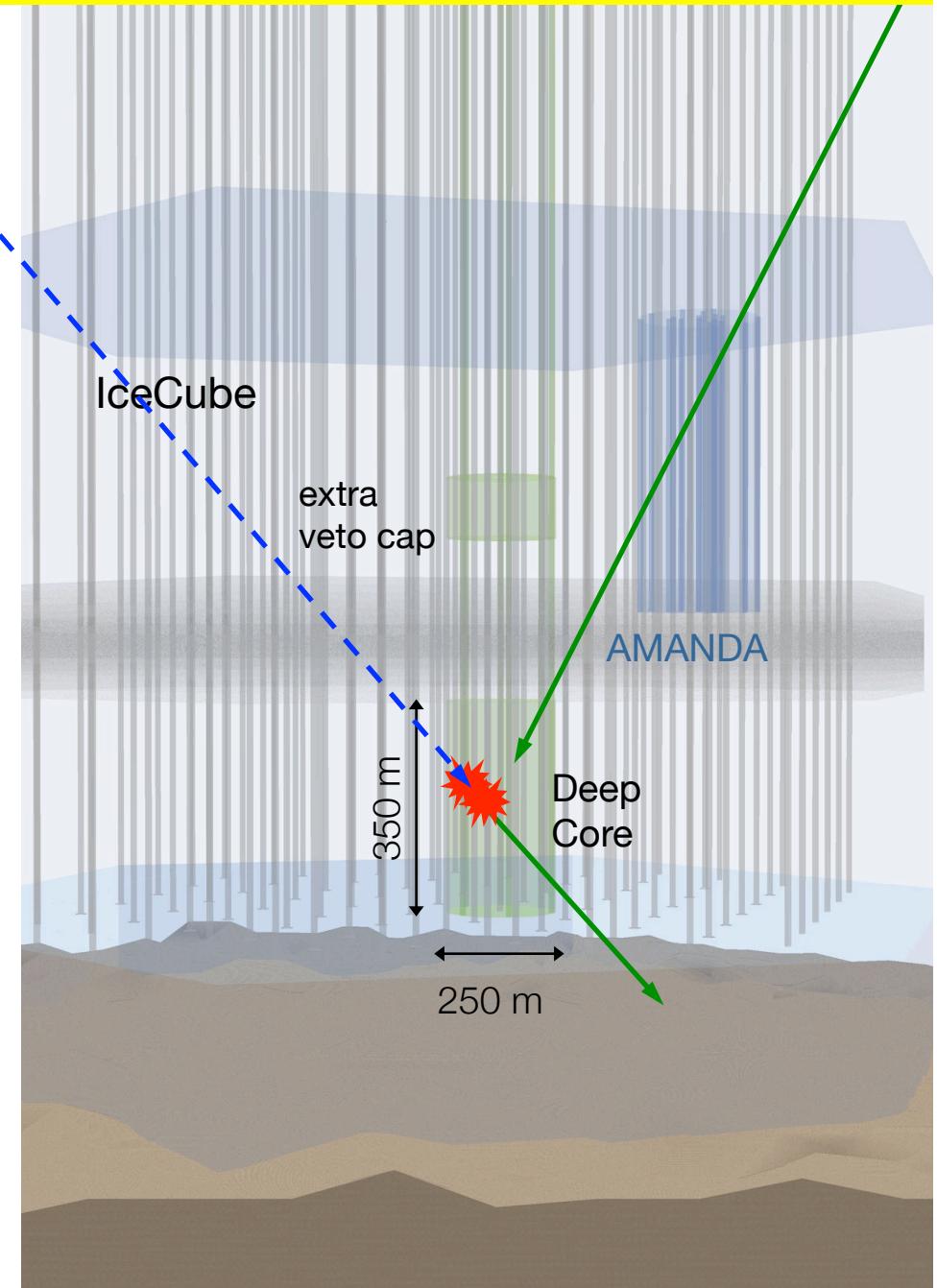
IceCube DeepCore:
10 GeV to 200 GeV

DESIGN

- Result: ~20 MTon detector with (compare SuperK: 20 kt)
- 100000 neutrinos/year

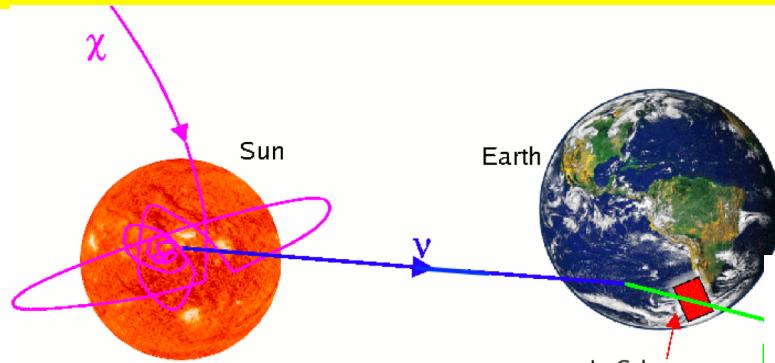
VETO

- Use IceCube strings to remove backgrounds
- Muon flux after veto lower than in deepest mines



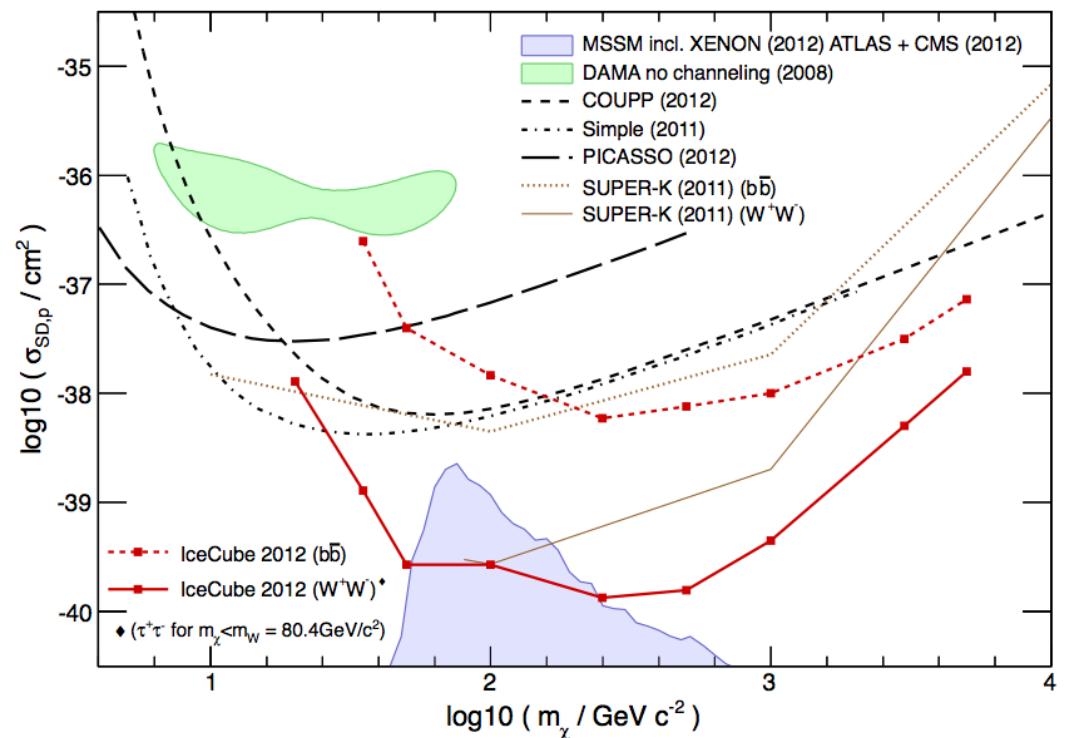
Dark matter: Indirect search, WIMPs in sun, galactic center,

Using IceCube-DeepCore (low energy subdetector)



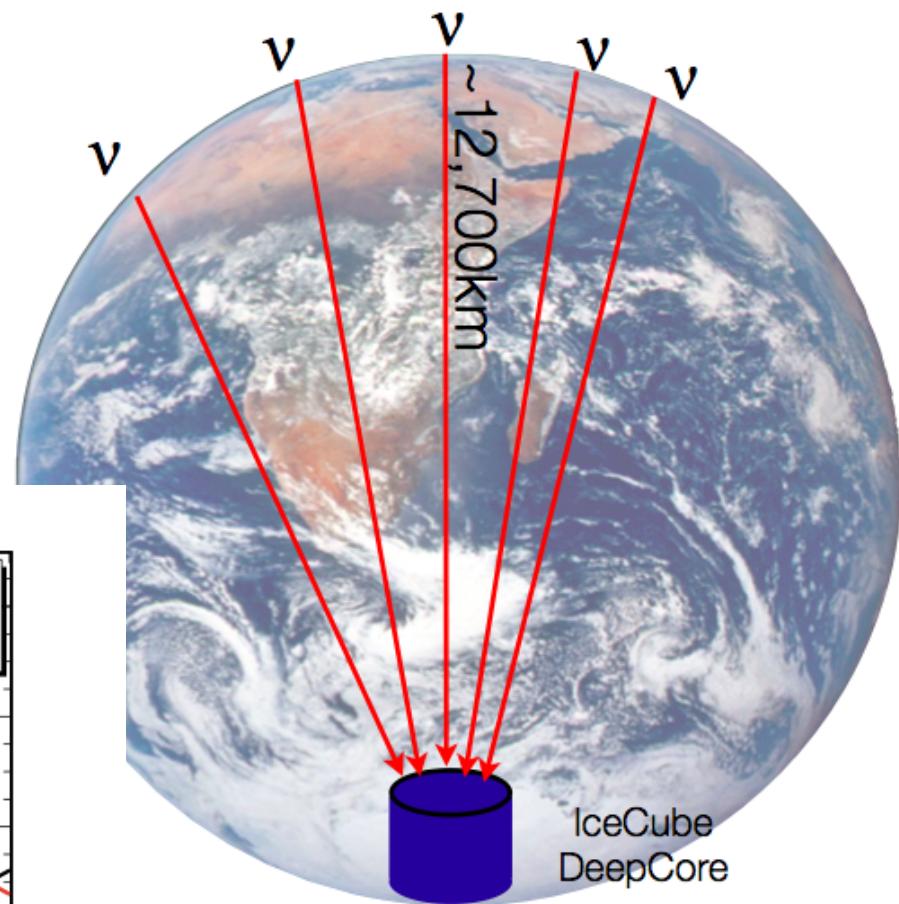
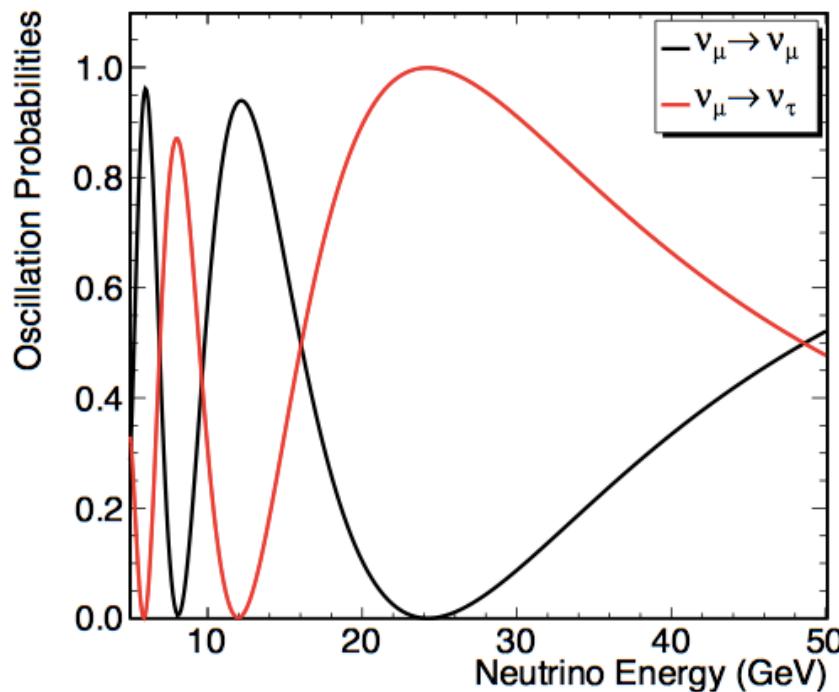
arXiv:1212.4097,
accepted PRL

- Dark matter accumulates in the sun, annihilating to high energy neutrinos
- Equilibrium annihilation related to solar capture rate
- → probes scattering cross-section
- Sensitivity from $20\text{GeV} \leq m_\chi \leq 10^7$
- High sensitivity to spin-dependent cross section due to proton target



Neutrino oscillation analysis with IceCube-DeepCore

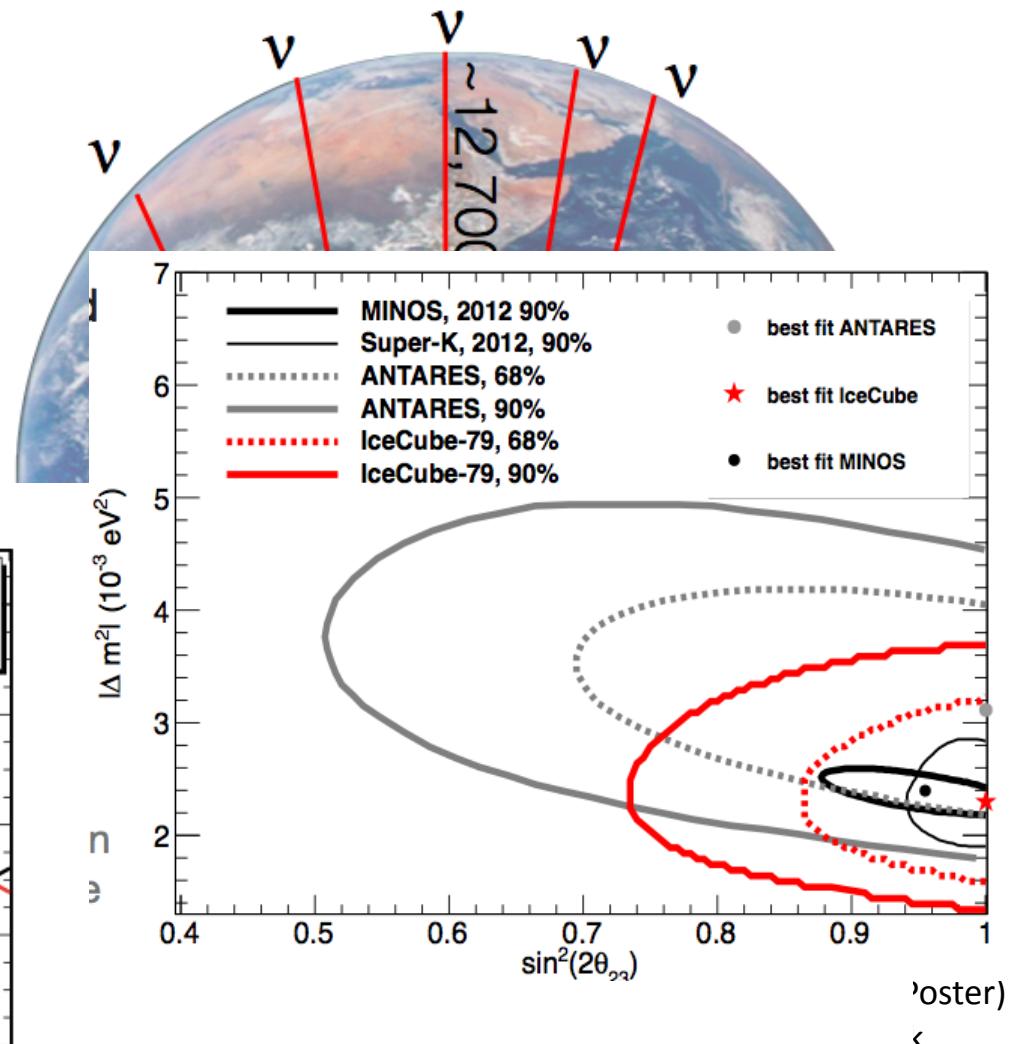
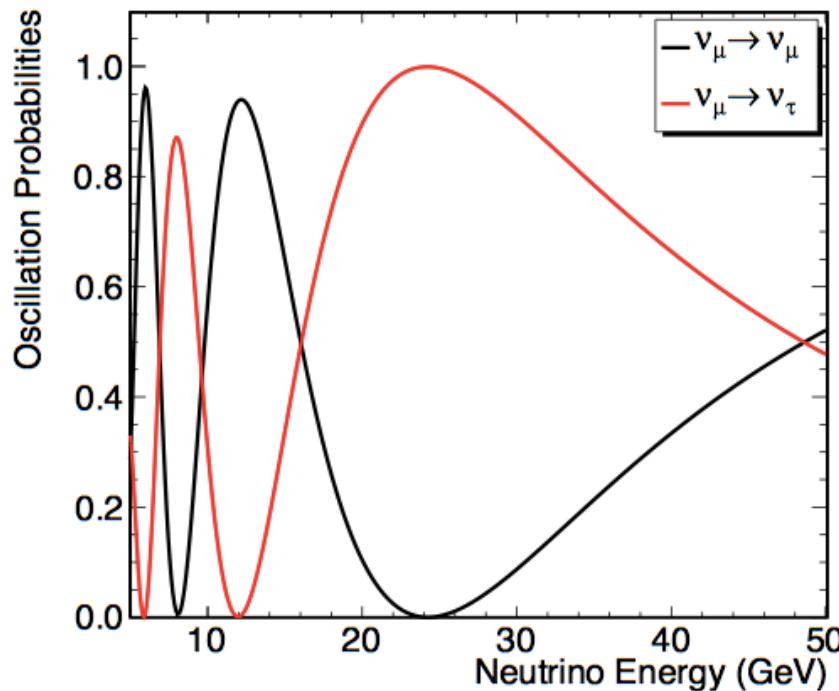
- First oscillation maximum around 24 GeV, i.e. DeepCore energies
- Hierarchy-dependent matter effects below 10 GeV – too low for DeepCore



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Neutrino oscillation analysis with IceCube-DeepCore

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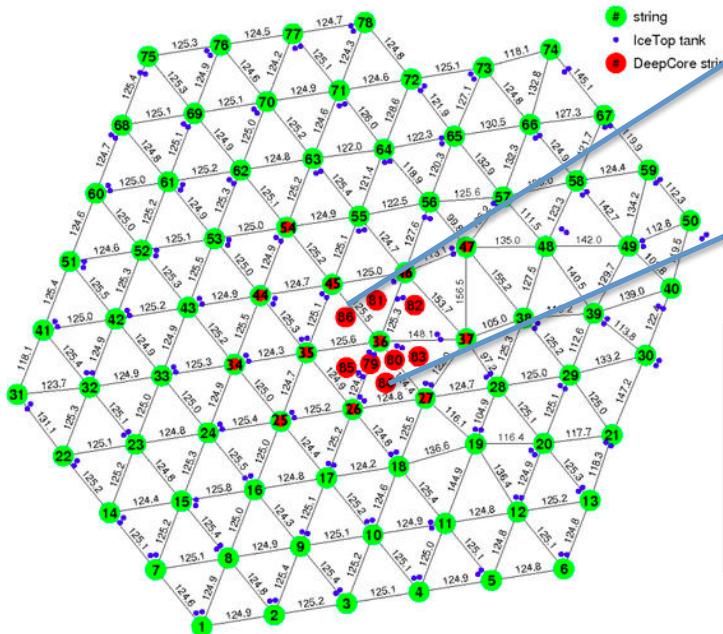


arXiv:1305.3909 (accepted PRL)

Extending this concept to lower energies

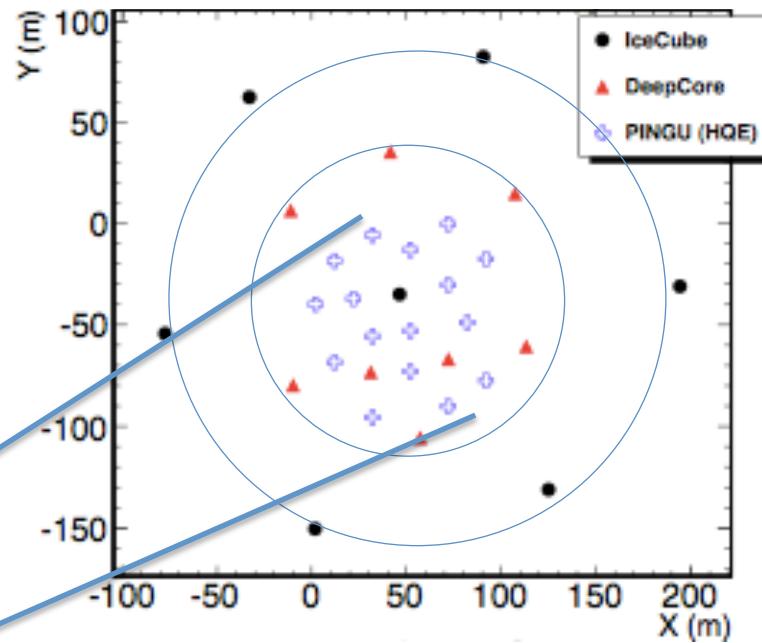
PINGU

- Precision IceCube Next-Generation Upgrade
- Add ~20 strings with ~1000 optical modules inside the existing Deep Core region (~500PMT)
- Expected energy threshold near 5 GeV



53

PINGU geometry (preliminary)

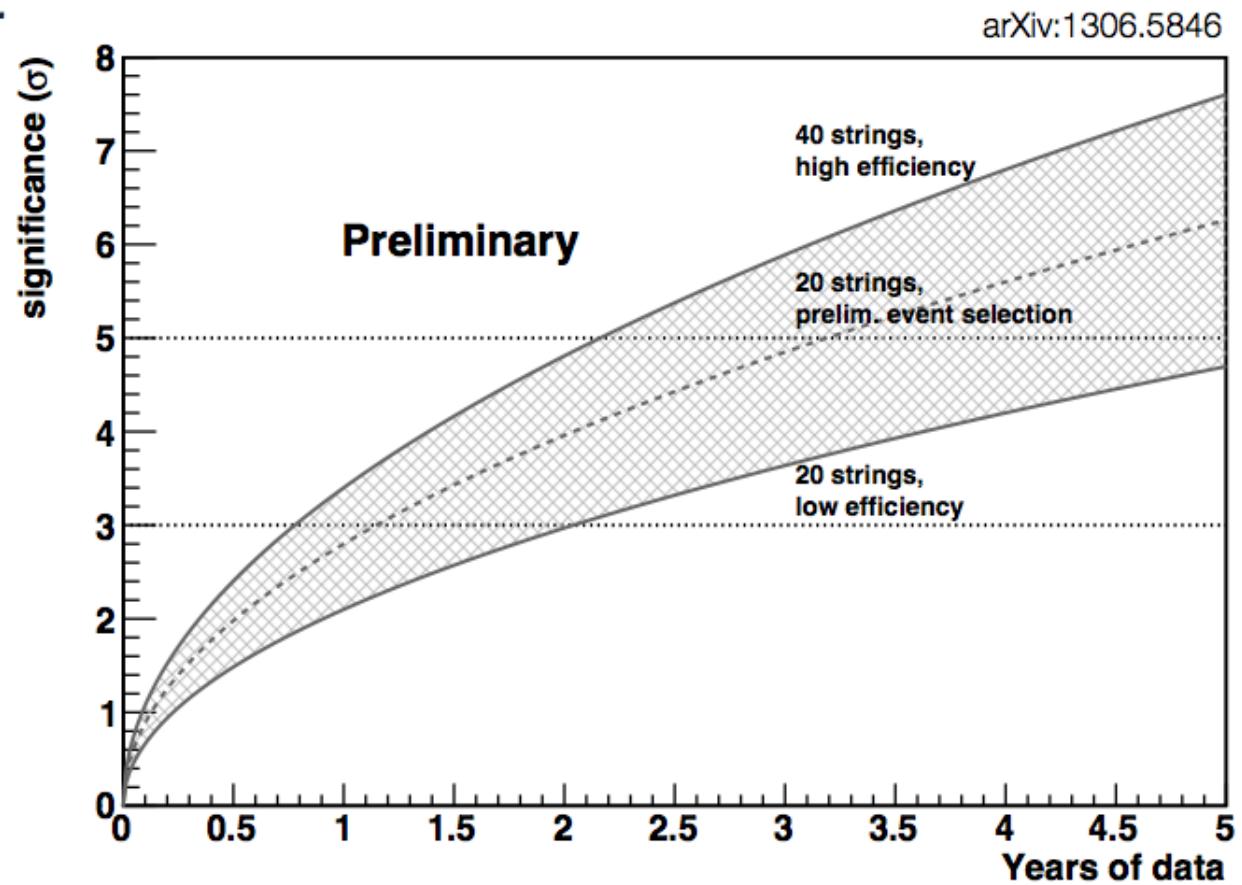


Currently studies underway to determine design to determining the neutrino mass hierarchy within 2 - 3 years.

PINGU Hierarchy Sensitivity

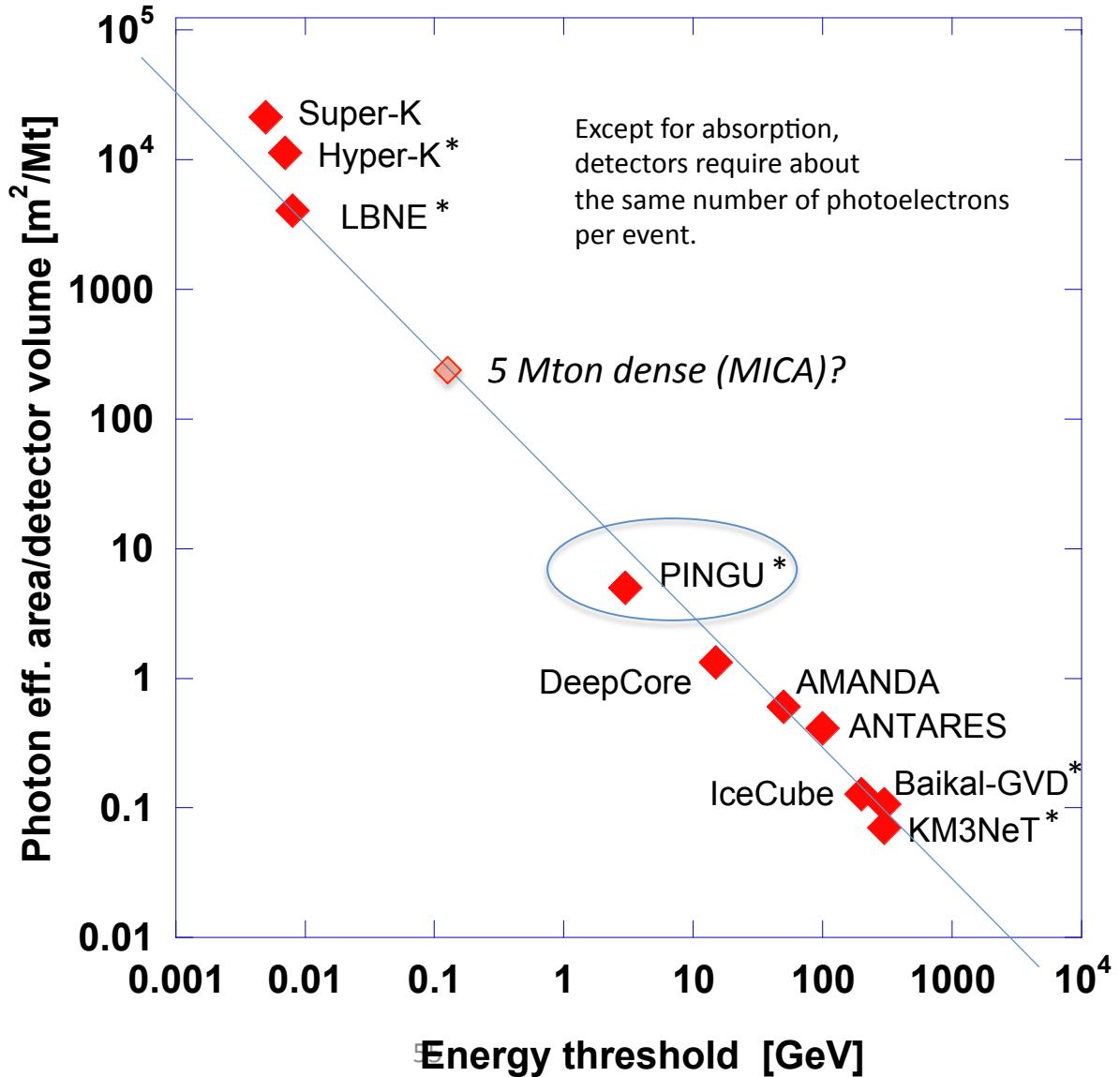
T. DeYoung at VLVNT

- Sensitivity depends on final detector scope, assumed analysis efficiency, detector resolution, etc.
 - Caveat: not all systematics included in each study
- Even with pessimistic assumptions, 3σ determination expected (median) with 2 years' data
 - 5σ in 2-4 more years
- Working now to refine details and extend systematic studies



Water Cherenkov detectors

PMT coverage vs threshold



Define:

Photon effective area =

Number of PMT

x Cathode area

x Quantum efficiency

= equivalent area of 100% photon detection.

(collection efficiency not included here.)

Photon effective area prop. $\sim 1/\text{Energy threshold}$.

Detector arrangements and optical properties of water and ice are different, yet the PMT density scales well with energy threshold.

*) design study or planning phase

Multi megaton detectors?

- Fundamental physics: proton decay
 - Lifetime $> 10^{34}$ years?
 - Connection to Grand Unified theories
- Astrophysics
 - Supernova neutrino detector with visibility to 5 Mpc?
 - See neutrinos from a supernova core collapse every year or every other?

Summary

- Two 1 PeV neutrinos observed at threshold of GZK searches (2.8σ)
- Follow-up analysis finds 26 more at lower energy (3.6σ)
- Increasing evidence for high-energy component at 4σ level beyond standard atmospheric backgrounds
- Indication in other analysis channels for hard component in neutrino flux
- Significantly more data being analyzed in very near future:
 - 1 more year starting track, 2 years diffuse muon neutrinos
 - Extend cascades to lower energies
 - Global fit, other
- Publication and more data coming soon



V

Systematic Studies and Cross-Checks

Cross-check with a fit method based on direct re-simulation of events

- Second fit method based on continuous re-simulation of events
 - Can include most complex description of ice (directional anisotropy in the scattering angle distribution and tilted dust layers)!
- Shown: comparison with other method
- Within these known bounds: all results are compatible to within 10%

